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TECHNICAL REPORT
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VIRTUAL PROTOTYPING FOR PERSONAL PROTECTIVE EQUIPMENT AND WORKPLACES

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13. ABSTRACT (*Maximum 200 words*) (REPORT DEVELOPED UNDER SBIR CONTRACT)
The Phase I effort developed a roadmap for development of a digital human model suitable for virtual prototyping of protective equipment and as a character in a virtual environment. The human model employs detail body contour data obtained from full body scanners onto which an anthropometrically accurate 3D digital model is created. Landmarks on the body surface are used to map internal anatomy. Mass properties of body segments and joint equations of motion are incorporated in order to describe body dynamics of the digital human. Models of protective equipment performance are extended to describe interaction of a range of military projectiles with multilayer soft fabric body armor, with and without rigid insets. Models of penetrating wounds from ballistic impact, blunt trauma from non-penetrating projectiles, and kinematic trauma will also be incorporated into the digital human model. Finally, a software architecture is developed which includes at least three design cycles. The first cycle is detailed static design which evaluates reduction of joint moment generating capability, thermal load, stability on various terrains, increase in work associated with movement, pressure points under different equipment loads, and casualty reduction potential to prescribed threats. The second cycle is a dynamic analysis, which includes the digital human accomplishing tasks with the equipment in a virtual environment. Parameters relative to equipment performance and the physical state of the virtual humans can be displayed as a function of time. Additionally, the dynamic analysis can be stopped at any point in the scenario to perform detailed static analysis of the digital human or to compare performance with previous dynamic simulations. The final cycle is non-virtual field testing.

14. SUBJECT TERMS

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PREFACE

This report describes the work done to develop a software development roadmap supporting virtual prototyping of personal protective equipment and workplaces. The effort was accomplished by the Department of Defense (DoD) and a contractor team. The DoD personnel belonged to the U.S. Army Soldier and Biological Chemical Command (SBCCOM), Natick Soldier Center (NSC). Contractor support was provided by Mission Research Corporation, Beecher Research Company and SA Technologies under Natick contract DAAK60-96-P-7029.

VIRTUAL PROTOTYPING FOR PERSONAL PROTECTIVE EQUIPMENT AND WORKPLACES

1. BACKGROUND

This Phase I Small Business Innovative Research Program (SBIR) effort was awarded to Mission Research Corporation (MRC) on 22 March 1996 by the U.S. Army Soldier Systems Command (SSCOM) at Natick, Massachusetts. The technical effort concluded 31 October 1996. Mr. John A. O'Keefe IV (SSCNC-AAM), was the Soldier Systems Command's Contracting Officer Representative. The objective of Phase I was to develop a Phase II software development roadmap, which supports virtual prototyping of personal protective equipment and work places. This report represents the final deliverable for this effort (Contract Data Requirements List (CDRL) 002).

1.1 Scope of Work and Task Descriptions

The phase I program included six technical tasks and one administrative task. The technical effort had a six-month period of performance. The first task, discussed in Section 2, focuses on developing improved models of protective equipment, in particular, improving the fidelity and generality of existing MRC analytical models, which predict protective equipment performance to ballistic insult and collateral battlefield effects. The second and third tasks are discussed in Section 3 and discuss development of a digital human model including anthropometry, anatomy, and articulation. The fourth task, discussed in Section 4 and entitled "Trauma Modeling," overviews a plan to incorporate advanced projectile penetration algorithms under development by MRC for the Advanced Biomedical Technology program at the Defense Advanced Research Projects Agency (DARPA). Also, a plan for improved blunt trauma modeling is presented. A software environment for visual implementation of the virtual prototyping system is provided in Task 5 and discussed in Section 5. Finally, a roadmap for Phase II development of the proposed tool is provided in Task 6 and discussed in Section 6. Brief descriptions of each task taken from the Phase I proposal are given below.

1.1.1 Task 1 – Protective Equipment

MRC has developed a soft body armor model as part of DAAK60-C-92-0008 that accurately predicts displacement time histories for non-penetrating blunt fragment and projectile impacts. This model, however, does not accurately predict failure and must rely on empirical data for this purpose. The model is also limited to multilayered fabric configurations over the human torso. The possibility of enhancing this model for ceramic inserts, sharp projectiles and fragments, and penetrating impacts will be investigated.

1.1.2 Task 2 – Anthropometry Development

A plan to enhance the anatomy and anthropometry of the MRCMAN code was developed. Specifically, a low-resolution version of the Visible Human data might be used to enhance anatomical fidelity. Also, enhancing the number of joints and including dependent joints as well

as having rigid links coinciding with bones in the body will be studied. A plan to include range of motion data and constraints relative to coupling of motion between joints will be prepared. Also, it is necessary to allow tissue to stretch around joints so gaps in the anatomy do not appear, thus joint motion will not entirely be rigid. Scaling options in all three dimensions will be investigated and designed to coincide with landmarks used in the Army Anthropometric Survey (ANSUR) database.

1.1.3 Task 3 – Body Dynamics

A plan to input mass properties and kinematic constraints between joints will be investigated. MRCMAN will be mapped to the Articulated Total Body Model source code so that equations of motions for the various body segments will be integrated into the virtual tool. Also, stability or balance algorithms will be incorporated, essentially identical to those included in *JACK*. Finally, methodologies to address spatial interaction with the workspace will be investigated.

1.1.4 Task 4 – Trauma Modeling

A plan will be rendered to incorporate advanced projectile penetration algorithms under development by MRC for DARPA. A plan to improve blunt trauma models will also be investigated. Currently, displacement-time histories of non-penetrating impacts to soft body armor over the thoracic cavity is used as a forcing function to a viscous dashpot model of the lungs to predict blunt trauma injury to the thoracic cavity. In lieu of a similar model for the abdomen, the Viano viscous criteria are used. The Viano model, however, is derived from car crash scenarios and although appropriate for certain blunt trauma injuries involving large anatomical regions with slow loading times and long durations, the criteria is probably not applicable to non-penetrating projectiles striking body armor. A plan to more comprehensively address blunt trauma and crushing injuries will be studied.

1.1.5 Task 5 – Scene Generation

MRC in consonance with the Government will identify desired computer platforms and a software environment for visual implementation of the virtual prototyping system. A plan for visual implementation of virtual prototyping tool and interaction with the work place will also be developed.

1.1.6 Task 6 – Phase II Planning

The main deliverable at the end of Phase I will be a roadmap for Phase II development of the proposed tool and an object oriented simulation architecture which supports rapid prototyping of the virtual design tool.

1.1.7 Task 7 – Preparation of Deliverables

Deliverables include three progress reports submitted every two months summarizing technical progress in relation to scheduled milestones and funds expended, a draft final report, and a final report.

1.2 Program Vision

Development of the virtual prototyping capability proposed in this effort will enhance the design of protective equipment in several new and innovative ways, as well as provide additional capabilities to the Army that can be exploited in training, mission rehearsal, operational scenario analysis, and the design of notional equipment other than protective equipment. The most interesting capability is perhaps provided by the visualization system, which will serve to integrate end users at the beginning of the design process. This promotes implementation of concurrent engineering to all interested parties at all levels of the design process. There are also many commercial implications to the proposed work.

In addition to providing enhanced models of protective equipment performance as overviewed in Section 1.1.1 and described in Section 2, the proposed effort would develop a digital human model that could interface with the protective system models. Various aspects of the digital human model and associated visualization system are discussed in Sections 1.2.1 through 1.2.4.

1.2.1 Digital Human Model

First, a digital soldier model will be developed with accurate body contours, anthropometry, and internal anatomy. Body contours will be based on highly resolved 3D models of actual soldiers obtained from body scans using a Cyberware® body scanner. External landmarks will be related to internal anatomical features, which will be used to map anatomical data onto the 3D-body model. This anatomical data will be obtained from the National Library of Medicine's Visible Human project (to the extent that it has been segmented) and MRC's existing *JOHN O.* (a.k.a. MRCMAN) model.

Currently, anthropometry data is based on linear measurements of fiducials on the body surface. These dimensions are then allocated to a database describing different percentile classes. In this way, for example, a 10, 50, and 90% percentile body can be obtained. Mannequins with exchangeable parts representing different percentile classes can then be used for "mock-ups" and assessing prototype fit. This approach has various shortcomings, however. First, existing anthropometric databases do not adequately account for *somatype*, that is, breadth, depth, and contour data and its correlation with the linear dimensions typically collected. Second, joint locations and centers of joint rotation relative to external landmarks are not known with adequate precision. Finally, there is no high resolution, integrated capability that explicitly models the relation between internal anatomy and external body surfaces. Currently this is done using intuition and is sub-optimal.

1.2.2 Fatigue, Trauma, and Injury

The digital human discussed previously will incorporate models of movement rate, cardiovascular fatigue, heat stress, penetrating wounds and blunt trauma. Estimates of allowable movement rates, cardiovascular fatigue, and heat stress will be obtained by either creating an interface with the Integrated Unit Simulation System (IUSS)[1] or directly integrating the appropriate government models (e.g., the Kranning and/or Goldman-Giovani models development by U.S. Army Research Institute of Environmental Medicine (ARIEM)).

Models of penetrating wounds are currently being developed by MRC for virtual surgery simulators under development by the Advanced Biomedical Technology program at DARPA.[2,3,4] This effort is basically a Phase III follow-on to MRC's Phase II development for Natick of the *Soldier Protective Ensemble Computer Aided Design* (SPE/CAD) system which includes the *JOHN O.* (MRCMAN) model.[5] Blunt trauma in the thorax and abdomen is currently evaluated in SPE/CAD using two approaches. First, a viscous dashpot model of the lungs[6] developed by the Lovelace Institute and resurrected by Larry Josephson at the Naval Weapons Center at China Lake has been incorporated as an SPE/CAD module. This model can predict intrathorasic pressure, chest wall displacement, velocity, and acceleration given a prescribed pressure time or displacement time-history on the surface of the chest. For non-penetrating blunt impact on body armor validated models of rear surface PASGT armor displacement time-histories have been developed by MRC and can be used as initial conditions for the viscous dashpot model.[7] Additionally for both abdominal and thoracic blunt trauma, the armor displacement-time histories can be used directly with the Viano viscous criterion[8] to predict blunt trauma injury to these body regions. This criteria, however, has only been validated for blunt trauma associated with pressure time-histories lasting tens of milliseconds and encompassing large areas of the body (i.e., car crash scenarios). Where as this approach is probably valid for kinematic trauma (i.e., where something falls on the soldier or the soldier is knocked against something), its application to ballistic impact remains uncertain.

Part of the difficulty is the lack of medical case histories or anecdotal information, which indicates the type of tissue damage associated with injury in these scenarios. The proposed effort will attempt to acquire this information from three sources. First, the United Kingdom has an extensive database of blunt trauma injuries from rubber and plastic bullets from which we will attempt to glean the necessary anecdotal information. Second, the Wounds Data Medical Evaluation Team (WDMET) database will be *mined* for these types of injuries as well as anecdotal information from the military medical community. Finally, the martial arts literature will be reviewed to extract threshold velocities and specific impulse at which damage occurs. MRC has already used this approach to determine threshold velocities and specific impulse to determine under what conditions the femur will fracture.

Once the type of tissue damage associated with this class of injuries has been established, local pressure fields promoted behind the body armor will be modeled. This activity is already taking place because of MRC's *Sensate Liner*[9] effort where MRC is experimentally determining and modeling pressure fields and acoustic signatures of different projectiles interacting with body armor and clothing for the purpose of developing a suite of sensors and expert software that will remotely conduct wound assessments and be integrated in future combat clothing. The evolved pressure fields can then be compared with ultimate values of tissue mechanical properties to determine tissue damage.

1.2.3 Motion and Articulation of the Digital Human Model

The proposed model will incorporate segment mass properties and joint equations of motion obtained from the Articulated Total Body Model (ATBM).[10] This will allow external forces from

weapon effects to evoke motion and displacements in the body for trauma assessment. The proposed digital human, however, will function in this environment in a relatively passive manner unlike *JACK*, which has the ability to do work in the environment for ergonomic evaluations. While incorporating the necessary biomechanical models into the proposed digital human model might be desirable for a virtual prototyping effort in order to assess task performance, two trade-offs mitigate against this. First, the requisite biomechanical models and input data are very immature and to some extent not validated. Second, incorporation of these models imposes a massive computational burden making these models unsuitable for a real-time simulation environment.[11]

Problems with the biomechanical approach for animating motion are at least threefold. First, there are no models that accurately characterize accommodation to a design if two or more body dimensions are critical. In fact, data relative to range of motion in other than principal body planes, particularly involving combinations of joint motions and independent axial rotations are almost non-existent. Second, human muscle strength is highly idealized. It is usually measured under static ("isometric") conditions (i.e., body does not move and muscles remain at same length) which is only weakly related to dynamic exertion of strength. Alternatively, human muscle strength may be idealized as isotonic (i.e., muscle strength remains constant) which is equally unrealistic. Finally, the interaction of the protective equipment with the body surface under dynamic conditions (that is while the body moves) is currently analytically intractable. Given the tremendous variety of human sizes, shapes, performance capabilities and limitations, analytical models entailing the capabilities above are of limited utility at the present time and do not argue for incorporation and the necessary investment of computational resources which would compromise performance of other capabilities.

Animation in the visualization system will be achieved by body scanning soldiers in a series of "key" postures, with and without loads, and interpolating joint angles as a function of time to create a smooth sequence of "in-between" postures.

In the proposed virtual prototyping system, the reduction in the joint moment generating capability (as opposed to an absolute value) will be modeled by increasing the mass and diameter of links between joints in the body model and adjusting the mass properties appropriately. This does not allow motion of the equipment over the body surface but represents the state-of-the art at this time. The shift in body center of gravity produced by the perturbation in mass properties will be used to model stability on different terrain. The stability algorithm will be essentially identical to the algorithm used in *JACK* where the center of mass of the body and equipment will be constrained to lie along a line above the figure's support polygon. We do not anticipate, however, including a "balanced reach" behavior at this time as does *JACK* (i.e., when one foot of *JACK* is constrained to remain on the floor and *JACK* reaches for something with a hand, the other foot lifts off the floor to counterbalance the motion of the hand and maintain balance). It is our assessment that the requisite algorithms and model data would entail a significant computational burden without a commensurate benefit in enhancing the virtual design process.

High pressure regions along the body surface under different equipment load states can be modeled as well as thermal loads, mechanical work expended, multispectral signatures, and some semblance of range of motion encumbrance.B

1.2.4 Visualization System and Software Architecture

The design of protective equipment as conceived of in this effort has three basic cycles: static design, dynamic design, and field testing. In each of these phases, the application of 3D visualization can be used to improve the design process.

During static analysis, various factors are evaluated and engineering trade-offs are made. The design of personal protective equipment must balance factors of wearability, durability, and overall effectiveness of protection. Successful completion of the proposed Phase II effort will provide a significant increase in the amount and quality of the data available to the designer. To make effective use of this influx of data, the designer needs improved tools to evaluate the results of trade-offs made during each design iteration. Using 3D modeling and rendering, as proposed in this effort will provide the foundation for such a tool set.

Wearability is a function of several factors such as mass distribution, abrasion, heat transfer, and flexibility. The 3D image will provide the designer with color coded representations of how the proposed equipment interacts with a representative selection of wearers. Given the current and short term analysis capability, the main factors to be evaluated at this stage are reduction in joint moment generating capability, increased work load during movement, stability on different terrain, mass distribution, total weight, thermal load, and casualty reduction. As analytical models of human mobility and range of motion improve, these factors can be incorporated into this phase of the analysis.

Combining analytical models of mobility and range of motion with material property data will allow evaluation of protective equipment for durability. Improved durability can be obtained by identification, as early in the design cycle as possible, of points of high stress or wear. This information permits the designer to select materials and construction techniques with greater value and performance at a lower cost.

The overall effectiveness of personal protective equipment is a balance of the greater encumbrance imposed by the equipment versus the higher probability of mission completion through reduced casualties. Here again, 3D imagery can be used to assist in the design process. This is accomplished by identifying the range of threat environments in which the equipment is to be used, and the distribution of injury severity and type, which can be expected in those environments. This is then translated into a visual model indicating areas of the body at greatest risk to different types of injury (i.e., penetrating wounds and blunt trauma). The designer can then interactively apply protective material, in a selective manner, until an acceptable risk level is reached. The designer can thus use a minimum of mass, thereby reducing encumbrance, while still providing the maximum level of protection at a given cost point.

Once a cycle of static design is competed, a dynamic analysis is needed to validate the conclusions of the static analysis. The dynamic analysis looks for such features as significant changes in bulk, which would affect the selection of cover or access to confined spaces. Significant changes to endurance, due to better heat transfer or reduced mass, could effect the selection of tactics. The dynamic analysis would take synthetic actors/combatants through a series of scenarios. Each run would be scored against a baseline simulation. The simulation would be controlled by a combination of self-directed characters and a human director who could make use of new tactical opportunities.

The static analysis provides the designer with statistical data on the type and distribution of impacts from which the equipment is suppose to protect the wearer. The dynamic analysis will demonstrate that the original threat model is consistent with the manner in which the equipment is used. The results of these tests would be passed back to the static analysis to provide a more complete analysis of the protective equipment.

When the design is approaching the point where prototype equipment is to be built, a virtual environment can be used as a final human factors check of the protective equipment. This serves as an intermediate step between theoretical analysis and actual field testing. At issue is the response of teams using the new equipment.

Given a threat environment, a team using baseline equipment would normally select one of several tactical solutions to resolve the situation. Since no solution to a combat situation is risk free, every solution must be evaluated on a statistical basis, weighing team losses against mission success. By substituting the proposed protective equipment, new tactical options can be evaluated as well as changes to loss rates using conventional tactics.

By running a number of simulations in a virtual environment, the evaluators can quickly develop an appreciation of the new equipment's strength and limitations, even before the prototypes have been fabricated. By the time actual field testing begins, the group doing the evaluation has had an opportunity to develop a more comprehensive set of tactics to apply. This should result in shorter, more effective field testing. A unique advantage of this visualization system is that it provides a common basis in which to integrate Army field officers early into the design process taking concurrent engineering to its logical conclusion. A virtual environment under development by MRC that can be used for this purpose is described in Section 1.3.

1.3 STRICOM Phase II SBIR

The Fountain Valley, California office of Mission Research has been awarded a FY97 Phase II SBIR from the U.S. Army Simulation, Training, and Instrumentation Command (STRICOM) in Orlando, Florida. The purpose of this SBIR is to incorporate real-time simulation of weapons effects (small arms, grenades, explosive satchels) into a Distributed Interactive Simulation/High Level Architecture (DIS/HLA) compatible urban warfare virtual environment. The virtual environment under development consists of a "precision" building clearing operation using a digital McKenna Town Hall building from the Fort Benning MOUT site.[12]

1.3.1 Highlights of STRICOM Phase I SBIR

The STRICOM Phase I effort identified key problems and relevant approaches for Phase II. Moreover, fundamental modeling and simulation (M&S) issues which extend beyond the current application were addressed; i.e., how to embed modeling of physical processes (which is necessary if the objects in a simulation are to interact in a non-scripted manner) in real-time visual simulations. During Phase I, a "precision" MOUT scenario for clearing a building was developed. This scenario included interior and exterior construction details, weapons and ammunition, soldier tasks and engagement ranges. Ballistic experiments were conducted on selected weapon-target combinations to identify interaction dynamics, and provide data for texture maps and analytical models. A sub-real-time code describing external and terminal ballistics of small arms was developed and correlated with experimental data. A stochastic model was developed to describe distribution of glass fragments from an incident blast wave. An approach was developed to describe structural integrity in explosive weapon effects environments using parametric solutions from hydrocodes and handbook solutions. A sub-real-time methodology using the MRC *JOHN O.* digital human, which will be interfaced with the Phase II virtual environment, will be employed to describe weapon effects on personnel. Finally, a digital fly-through model of the McKenna Town Hall was developed and various weapon effects were statically simulated.

It is intended that the digital human model being developed for the virtual prototyping system discussed in this report will be able to function as an enhanced character simulator in the STRICOM virtual environment. This will provide an intermediate step in protective system prototype development between theoretical analysis and field testing. Relevant "ground rules" for development of the STRICOM virtual environment will be followed in the Natick effort to ensure compatibility of the software.

1.3.2 STRICOM Phase II SBIR Software Architecture

Figure 1 shows the software architecture of the STRICOM virtual environment where grayed areas indicate the focus of the STRICOM effort and extensions to the state-of-the art. Non-grayed areas indicate existing off-the-shelf solutions that will be exploited and adapted.

The overall structure will be designed to execute as a single UNIX process. However, in an environment with more than one processor available, various secondary processes can be forked to permit better real time performance. We will build a hardware environment with multiple SGI Indigos and a SGI High End Impact for development purposes. Toward the end of the effort, we will export the software to a STRICOM or Natick hardware environment with higher end platforms to verify real-time performance and visual fidelity.

We intend to provide an environment with multiple characters interacting (initially two, this is merely limited by the number of processors and input devices available).

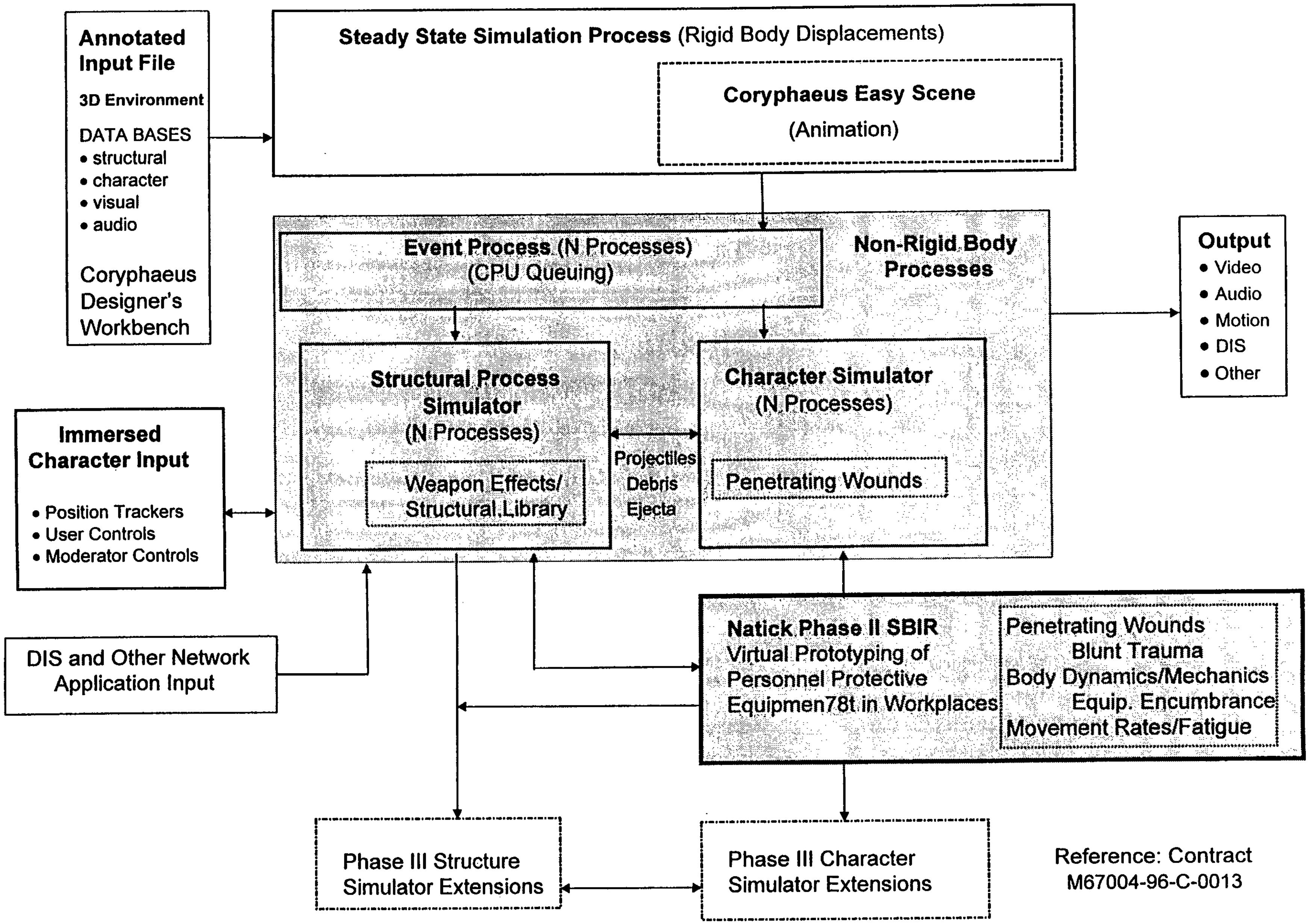

Figure 1. STRICOM Phase II Software Architecture

For any simulation system there has to be a core structure which maintains the real time state of the simulated environment. Using *EasyScene*™ from *Coryphaeus*™ *Software* will provide a foundation on which to build the "Steady State Simulation Process". *EasyScene* will provide real time video output from an SGI platform. *The Steady State Simulation Process* controls all of the routine simulation effects, which only require translation and rotation of objects (Rigid Body Motion) contained in the database.

An "event" is defined to be any occurrence in the simulation, which *may* physically alter one or more "atomic structures" in the database (Non-Rigid Body Deformation). An atomic structure is defined to be one object or group in the database, which has a defined structural composition (e.g. a window or a wall panel).

When the Steady State Process detects that an event has occurred, the event is queued for handling by an "Event Process." There may be more than one Event Process available to handle events, depending on the system resources available. Some Event Processes will require a dedicated CPU to maintain real time performance.

The function of the Event Process is to evaluate the nature of the event and the database environment in which it occurred. From the center of the event, the environment is evaluated and any atomic objects, which may be affected by the event, are queued. The interaction of the object and the event not only affects the object, but also may alter subsequent objects that are being checked. This permits shadowing effects for blasts and the determination of penetration effects of firearms.

The Event Process determines those objects which will be affected first (the objects closest to a blast or adjacent objects in the line of fire) and queue the appropriate combinations of "Structural Processes" and "Character Processes." After these processes have evaluated the effect on themselves and the affect of the event, the data is returned to the Event Process. If the event can still affect another object, the next object is queued for evaluation. This continues until the effect of the event dissipates.

The Structural Process has two functions, determine the effect of an event, and create a new visual representation of the object, as it would appear after the event. The visual representation is made up of two parts, the permanent representation and any transient effects (e.g. dust, smoke, and debris). The updated visual representation is passed back to the Steady State Process for rendering.

1.3.3 Relationship of STRICOM and Natick Phase II SBIR Efforts

The base requirements for the Character Process are the same as the Structural Process with the addition of character animation and biomechanical functions. These biomechanical functions would be emphasized in the Natick Phase II SBIR (see interface between Natick and STRICOM effort as represented in Figure 1) and developed to a much higher level of sophistication and fidelity than in the STRICOM effort. Similarly, the STRICOM effort would emphasize the structural processes to a much higher level of fidelity and sophistication than in the Natick effort.

Since the STRICOM virtual environment emphasizes the development of weapon effects simulation, it represents an ideal virtual environment for assessment of prototype protective equipment.

2. EXTENSION OF BODY ARMOR INTERACTION ALGORITHMS

Personal protective ballistic armor made from layers of nylon, Kevlar®, Spectra® and other advanced fabrics, with and without ceramic inserts, are currently being designed and fielded. For optimal design, the ballistic characteristics of such materials when utilized in multilayered assemblies need to be clearly understood. Key ballistic characteristics include ballistic limit, high and low-strain modulus, and strain to failure.

In controlled laboratory experiments features of the projectile penetration process are observed for single layers of such materials. The extension of methods and results obtained from the analysis of a single layered medium is discussed when multilayered configurations of these materials are used in developmental body armor. An overview of important results from the penetration mechanics of a single layered fabric material is also first discussed below as background.

One of the most important features in the impact analysis of such armor is the development of two distinct wave speeds in the fabric, one traveling with the acoustic wave speed of the fabric and other with an apparent transverse wave speed. At the end of the apparent transverse wave front, a change in particle velocity occurs indicating a change in acceleration. The observed physical phenomena can be explained as follows. A particle on the fabric away from the impact point first sees the arrival of a longitudinal wave causing the particle to move towards the impact point. Assuming that the fabric is initially on a horizontal plane, this horizontal particle motion begins to stop when the transverse wave arrives at the new displaced particle location.

At this point in time the particle now begins to move vertically along the direction of motion of the projectile with a velocity equal in magnitude to the instantaneous velocity of the projectile. If we assume that the magnitude of the fabric tension is continuous during the change in velocity, a relationship between the velocity jump and the fabric tension can be established using the particle equation of motion. These wave speeds are also dependent on the strain of the fabric at the time considered. This is unlike a solid material where bending can occur. The deformed shape of the fabric at any given time can be idealized as a cone (see Figure 2).

To mathematically describe the above process for multilayered configurations, we introduce the nomenclature in Table 1 and the following notation to indicate the parameters at any time t for the *n-th* layer ($n=1,2,.....N$), where N is the total number of fabric layers used in the armor.

These quantities are related through the equations shown in Table 2, which can be established from the definitions of these quantities and their kinematic relations.

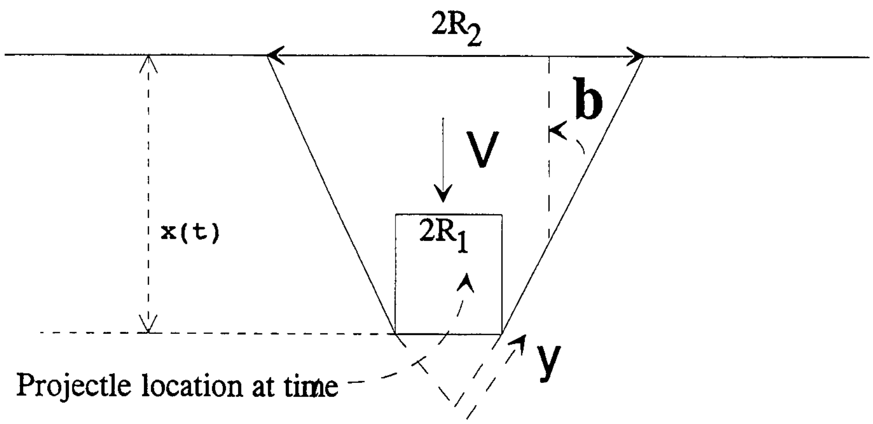

Figure 2. Deformed Shape of Fabric due to Projectile Impact

Table 1. Nomenclature for Analysis of Multilayered Configurations

c_n = Sound wave speed in the layer
$E_n = E_n(\varepsilon)$ = Strain-dependent Elastic modulus of the layer
T_n = Tension in the layer
ε_n = Average elastic strain in the layer
m_n = Circumferential mass per unit length in the layer
σ_n = Average layer stress
ρ_n = Layer density
u_n = Transverse wave speed in the layer
$\overline{u}_n$ = Apparent transverse wave speed in the layer
β_n = Semi-cone angle of the deformed shape of the layer
$V = \dot{x}$ = Instantaneous projectile velocity
w_n = Particle velocity
A_n = Circumferential cross-sectional area of the projectile footprint on the layer
R_1 = Projectile footprint radius

Table 2. Derived Relations for Quantities in Previous Table

$$c_n = \sqrt{\frac{E_n}{\rho_n}} = \sqrt{\frac{(\frac{\partial T}{\partial \varepsilon})_{\varepsilon=0}}{m_n}}$$

$$u_n = \sqrt{\frac{\sigma_n}{\rho_n(1+\varepsilon_n)}} = \sqrt{\frac{T_n}{M_n(1+\varepsilon_n)}}$$

$$\bar{u}_n = (1+\varepsilon_n)u_n - w_n$$

$$w_n = c_n\varepsilon_n$$

$$T_n = \sigma_n A_n = E_n A_n \varepsilon_n = \rho_n c_n^2 A_n \varepsilon_n = m_n c_n^2 \varepsilon_n$$

$$u_n = c_n\sqrt{\frac{\varepsilon}{1+\varepsilon_n}}$$

$$\bar{u}_n = c_n[\sqrt{\varepsilon_n(1+\varepsilon_n)} - \varepsilon_n]$$

$${}_n = \sqrt{(1+\varepsilon_n)^2 u_n^2 - \bar{u}_n^2} = c_n\sqrt{2\sqrt{\varepsilon_n^3(1+\varepsilon_n)} - \varepsilon_n^2}$$

$$\varepsilon_n = \frac{V^2}{4c_n^2} = \frac{\dot{x}^2}{4c_n^2}\text{, for small } \varepsilon_n << 1 \tag{1}$$

In Equation (1), see Table 2, ε_n represents the average strain in the layer. The actual distribution of strain in the layer, from the projectile footprint outwards, shows significant stress enhancement due to the fabric layer wrapping around the projectile, a phenomena that has been observed in experiments.[13] When all layers have identical properties, MRC code MRFAB[14] can calculate the retardation of the projectile from Equation (1) and the differential equation of motion for the projectile.

From the previous discussion, two possible stacking sequences of two material layers and their interactive deformation geometry, are shown in Figure 3 and Figure 4. In these drawings, the softer of the two materials indicates that the integral of the apparent transverse wave speed over time is larger. The general deformed geometry of the multilayered assembly is shown in Figure 5 and the free body diagram of the projectile is shown in Figure 6.

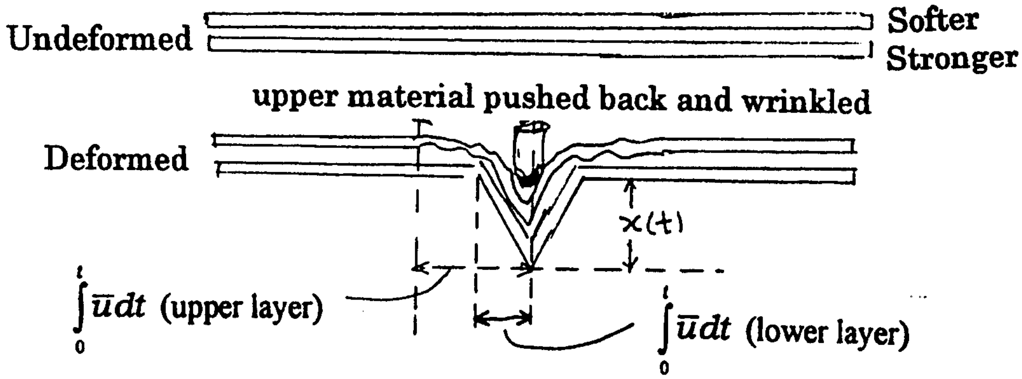

Figure 3. Softer Layer over Stronger Layer

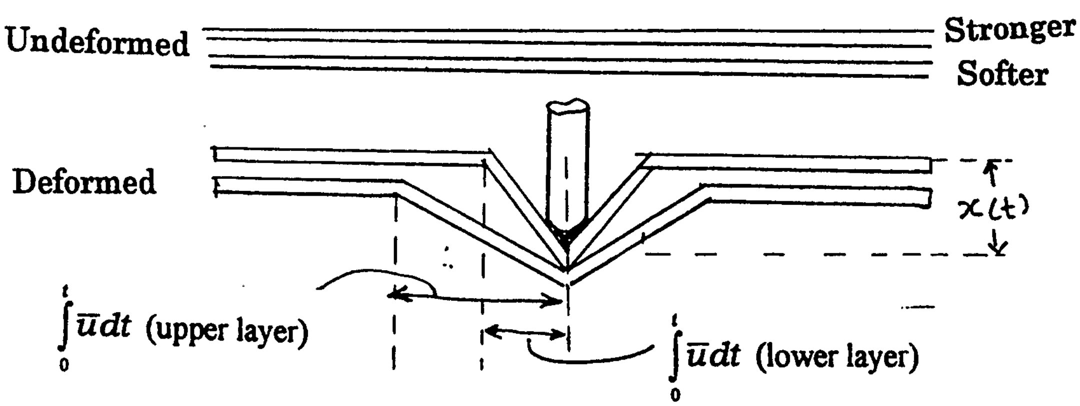

Figure 4. Stronger Material Layer over Softer Layer

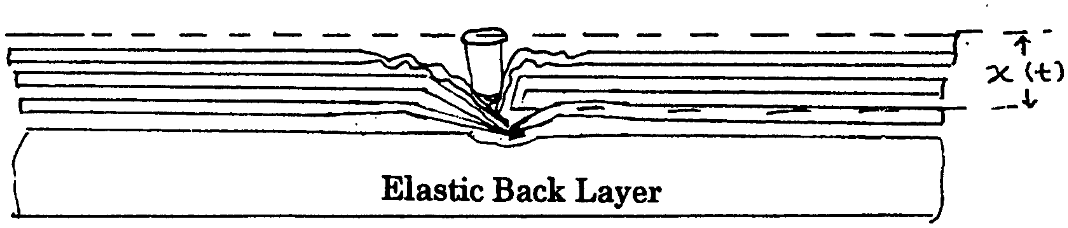

Figure 5. General Deformed Shape of Multilayered Configuration

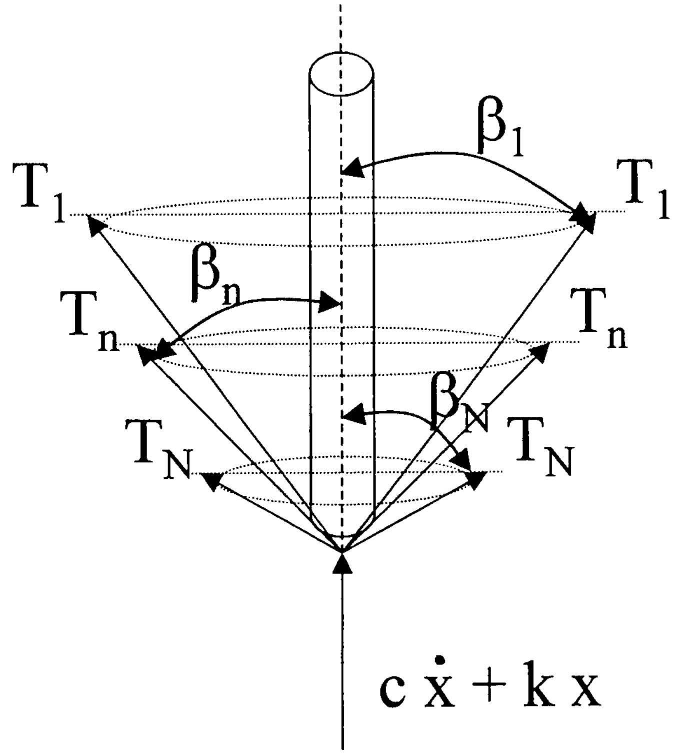

Figure 6. Free Body Diagram of the Projectile Interaction

From the free body diagram shown in Figure 6, the equation of motion of the projectile is given by

$$m_p\ddot{x} = -\sum_{n=1}^{N} T_n(\varepsilon_n)\cos\beta_n - c\dot{x} - kx \qquad (2)$$

In Equation (2), N is the total number of layers in the armor and ε_n depends on the instantaneous projectile velocity, $\dot{x}$, as shown in Equation (1). In Equation (2), constants c and k represent the equivalent damping constant and the stiffness of the elastic backing, respectively.

Equation (2) gives the nonlinear differential equation of motion of the projectile. At the time of impact of the projectile with the armor, the time is initialized. The solution for the field quantities at any time *t* can be obtained by numerical calculations using the algorithm shown in the following steps. In using these steps, it is assumed that for the armor under consideration, E_n vs ε_n data is known *a priori* for all layers ($n=1,2,....N$).[15]

1. At the start of the penetration process it is assumed that layer strains are small. For the *n-th* layer and for small strain, ε_n, Young's modulus, E_n, is calculated from known experimental data.
2. The sound wave speed, c_n, is calculated from $c_n = \sqrt{\frac{E_n}{\rho_n}}$.

3. Since the impact velocity $v_p = V$ is known, we can use Equation (1) to calculate the strain from $\varepsilon_n = \dfrac{V^2}{4c_n^2}$

4. The apparent transverse wave speed, $\overline{u}_n$, can now be calculated from Equation (1) since the strain, ε_n, and the sound wave speed, c_n, are known.

5. A time interval is then selected.

6. Initially, $\overline{u}_{n0} = 0$

7. From known $\overline{u}_n$, the outer cone radius, R_{2n}, (Figure 2) is calculated from $R_{2n} = R_1 + (\overline{u}_n - \overline{u}_{n0})\Delta t$

8. The projectile displacement, u_p, is calculated from $u_p = v_p \Delta t$

9. The semi-angle, β_n, of the deformed cone in the n-th layer is calculated from

$$\beta_n = \tan^{-1}\left(\frac{R_{2n}}{u_p}\right)$$

10. The projectile deceleration, $d_c = -\ddot{x}$, is calculated from equation of motion (Equation 2)

11. The new projectile velocity, v_p, displacement, U_p, and deformed cone radius, R_{2n}, are now calculated from

$$\left(v_p\right)_{t+\Delta t} = \left(v_p\right)_t - d_c \Delta t$$

$$\left(U_p\right)_{t+\Delta t} = \left(U_p\right)_t + v_p \Delta t - \frac{1}{2} d_c (\Delta t)^2$$

$$(R_{2n})_{t+\Delta t} = (R_{2n})_t + (\overline{u}_n - \overline{u}_{n0})\Delta t$$

12. Reset $\overline{u}_{n0} = \overline{u}_n$

13. Steps 1-12 are repeated until either the projectile stops or the fabric suffers a failure due to a critical strain criterion.

It should be noted here that due to the inhomogeneities in the layer properties, the strain, ε_n, in the *n-th* layer also depends nonlinearly on the strains in other material layers. Hence, the possibility of failure of some material layers due to exceeding a critical strain criterion may be realized while other layers in the armor may remain undamaged. This has been observed in many ballistic experiments conducted at MRC.

Using the assumption that the mass in each layer under the projectile footprint is negligible in comparison with the mass of the projectile, a non-zero semi-angle, β_n, of the deformed cone ensures layer contact below the projectile footprint. Thus, at any time, *t*, all terms in the summation in Equation (2) contribute to the projectile deceleration. The solution of Equation (2) also provides the tensions, and hence the stresses and strains in each layer in the armor due to the relations given in Equation (1).

3. ANTHROPOMETRY AND ANATOMICAL MODELING

This section, which is divided into four subsections, discusses anthropometric and anatomical issues of modeling the human body for a virtual prototyping tool. Subsection 1 discusses anatomical and anthropometric requirements. Subsection 2 discusses available software and databases for human body modeling to address requirements from the previous subsection. Subsection 3 overviews issues associated with modeling the fit or interaction of protective equipment with the human body. The final subsection discusses applications of the virtual prototyping tool. Table 3 lists software alluded to in this section as well as sources and summary descriptions.

Table 3. Software Discussed in Section 3

Name	Source	Description
ATBM	US Air Force Armstrong Lab at Wright Patterson AFB	3D human dynamics model
GEOBODIII	Beecher Research, Dayton, Ohio	Creates body model for ATBM
Shape Analysis	Beecher Research	Measures and compares 3D data sets
VOXEL-MAN	University of Hamburg Germany	Volume data of segmented internal structures
MAM	U.S. Air Force	Multivariate anthropometric modeling program
JACK	University of Pennsylvania	Human environmental model
COMBIMAN	U.S. Air Force	3D cockpit accommodation program
Crew Chief	U.S. Air Force	3D Workspace modeling program
FRNKNSTN	Beecher Research	3D human simulation using digitized subjects
John O. (a.k.a. MRCMAN) module of SPE/CAD	Mission Research Corporation Fountain Valley, CA	Human phantom incorporating trauma models and internal organs and tissue

3.1 Human Model Biofidelity

Biofidelity refers to the biological realism of the mathematical, or computer, model of the human body. In the past, available technologies were at best limited to developing prototype human-use equipment or workspaces in a two-step process. First, information on human measurements was analyzed to create ranges representative of the variety of sizes and shapes thought necessary for accommodation. Second, physical prototypes were created for those size/shape ranges. For instance, in creating headform sizes, linear measurements of servicemen's heads, such as length, breadth, and circumference, were analyzed to find the minimum and maximum ranges that would accommodate 95% of all servicemen. Then, the ranges were divided into a series of steps that defined the sizes. Finally, physical headforms were created that had the defined head

measurements. The biofidelity of the headforms was limited by the relatively few linear measurements used to specify their dimensions. Aspects of head shape not covered by the measurements were not part of the specification and the artist creating the headforms was free to interpret.

A method using more shape-related information, and thus more biofidelic, was used to create headforms for helmet sizing.[16] Here, movable probes in a shell over the subject's head were adjusted to record clearance at regular intervals. This information was also used to create physical headforms.

Depending upon the application – and availability of modern computers – full-body modeling has followed different paths to instill biofidelity in prototype development. In clothing and body protective equipment design, where sizing tends to follow traditional apparel industry models, data documenting the size and shape of military personnel was practically ignored until relatively recently. Civilian sizing still incorporates little or no body measurement data in design. Several early reports from Army anthropologists discussed the availability of detailed anthropometric surveys useful for design applications[17,18,19] and then despaired that the information was not used.[20] Designers were using traditional clothing industry methods and sizes to produce prototype articles which were then tariffed with little regard for the size/shape distribution of the customers. This practice changed in the last decade when available anthropometric data was used to produce sizing schemes and prototypes were systematically fit-tested on sample populations representative of the forces to be outfitted.[21]

Physical human models – anthropomorphic mannequins or crash test dummies – have been used to test prototype equipment, especially where there is some physical danger as in high-acceleration tests of aircraft escape systems. The biofidelity of these models has varied, but the aim of the designers has been to duplicate overall size and weight, not the details of joints, body segments, and internal structures. Detailed evaluation of state-of-the-art automobile mannequins showed that there was little similarity to any statistically representative human data model.[22] From these evaluations and taking advantage of all available 3D human body geometric, static, and inertial data, a series of mannequins was designed with as much biofidelity as possible, e.g., the *Advanced Dynamic Anthropomorphic Mannequins* (ADAM). Testing environmental conditions has also led to the construction of mannequins instrumented to measure conditions of environmental stress such as heat/cold and humidity.

Prototyping workspaces in military vehicles, such as aircraft cockpits, traditionally involved using a small sample range of a few anthropometric dimensions. On some aircraft, such as the T-38, two subjects, one large, one small, were used to evaluate accommodation in the cockpit.[23] While the *biofidelity* of the subjects would be unquestioned, the representation of flying personnel by two people (white males) left out a large amount of size and shape variability. More recently, physical prototypes have been subject to evaluation using more sophisticated statistical models of human size and shape distribution.

Workspaces are also being prototyped using computer models of both the space and personnel. Earlier models such as the *COMBIMAN*[24] had very simple representations of the workspace. The human model was represented by geometric shapes (cylinders, ellipsoids) for body segments, but it was based on available anthropometry (a 1968 survey of Air Force flying personnel) and so

had reasonable biofidelity. The model was intended to test cockpit reach and vision, but performance was not realistically or strongly correlated with real human performance tests. In a technical sense, *COMBIMAN* was in part succeeded by *Crew Chief*.[25]

Crew Chief was developed as part of the Air Force Computer-Aided Acquisition and Logistical Support (CALS) program called DEPTH, which sought to have computer prototypes of acquisitions which could model human-machine interactions in such areas as maintenance and performance. *Crew Chief* embodied a new approach to man-modeling by incorporating performance data into the model. Extensive tests of reach, vision, and strength on a sample of subjects representing anthropometric ranges in the Air Force were performed, and the results incorporated into the performance aspects of *Crew Chief*. This greatly improved the biofidelity of the model. Rather than depending on *creating* performance in a crude 3D world, the model used a real-world performance database to test the 3D world.

Best known among the human models now used for prototyping and testing is *JACK*, developed and maintained at the University of Pennsylvania. Three-dimensional objects in *JACK*, including humans, can be modeled in some detail, including body segments, surfaces, joints, surface characteristics and joint constraints, so that a high degree of biofidelity can potentially be achieved. *JACK* can be both a static and dynamic model. Given the flexibility of the model, internal body structures can also be modeled. The problem is that the representation of surfaces and objects requires much hand work in constructing – one cannot automate a transformation of human 3D data from, say, CAT scans or laser digitizer, to the *JACK* data format. This has inhibited the flexibility of *JACK* in representing real body size/shape distributions. A front-end program called *SAS* is supposed to input anthropometry and output re-scaled *JACK* bodies, but limited experience using SAS tends to indicate some reliability problems.[26]

Another direction in biofidelic human modeling was taken by the Articulated Total Body Model (ATBM), originally developed by the Department of Transportation[27] and now maintained by the United States Air Force (USAF)Armstrong Laboratory.[28] The ATBM was first and foremost a dynamic model developed to predict human dynamics in automobile crashes. Later applications have included aircraft cockpit and escape dynamics. In order to incorporate sophisticated and computationally intense equations of motion, the objects, including humans, are represented by simple geometric shapes – ellipsoids, cylinders, rectangular solids. This compromises the biofidelity of the human models in terms of surface representation, but permits modeling the dynamics of individual body segments more realistically than in other computer programs. The relatively simple geometric data structures permit easy construction of environments for prototype testing. Enhancing the biofidelity of the human models in the ATBM is GEBODIII, a program which computes body data sets based on actual 3D human body data, including joint locations and performance.[29]

A recent tool that could combine anthropometry, internal geometries, and dynamic properties into a human model useful for battlefield simulations is Mission Research Corporation's *JOHN O.* model (a.k.a. *MRCMAN* module of the Soldier Protective Ensemble Computer Aided Design System – SPE/CAD).[30] Development of this model was sponsored by Natick (DAAK60-92-C-0008) in a Phase II SBIR. Mr. John O'Keefe was the Natick project manger for this effort.

The human anatomy in *JOHN O.* consists of 80,000 voxels representing more than 250 tissue types. Nineteen body segments have external geometries composed of ellipsoidal slices. The jointed figure can be interactively placed in any position. Overall anthropometric scaling, which could be used to model representative soldiers, is currently limited. *JOHN O.*'s tremendous advantage for this application is its straightforward data structure for representing body geometries. This data structure could better accommodate increasingly comprehensive human 3D data, such as surface laser and internal MRI scans. Linked to an anthropometry generator, as proposed below, *JOHN O.* is a good candidate for a flexible human model for virtual prototyping.

Numerous other computer programs are capable of modeling humans in 3D for various limited applications, such as ADAMS/Android, Dench/ERGO, LifeForms, McDonnell Douglas Human Modeling System, ShapeAnalysis, and Musculographics, Inc., and Software for Interactive Musculoskeletal Modeling (SIMM). General purpose CAD packages, such as Alias Designer or ProENGINEER might also be adaptable to human modeling.

Previous efforts at prototyping – virtual or physical – have lacked the combination of data, software, 3D recording technology, and high-powered computer resources that are available today. The resources now available and those that are being developed in companion programs can be combined to produce human modeling capabilities with unprecedented biofidelity.

For this Virtual Prototyping effort, the human modeling aspect must have the following capabilities: (1) Background anthropometric database from which statistically generated data sets representing intended size and shape ranges of military personnel can be easily and automatically generated, (2) Geometries of internal body structures which can be scaled and organized to fit the anthropometric external geometry, (3) Database of physical properties of body tissues, organs, and segments including force-deflection and inertial properties, (4) Software to input the above resources and output a body model appropriate for the Virtual Prototype modeling software, and (5) Software module as part of the entire Virtual Prototyping system which can manipulate the body model, react to external conditions in the virtual environment, including trauma, and interface with the larger Virtual Prototyping software to communicate results of simulations. Figure 7 shows a proposed *roadmap* linking together databases and data analyses. Data and

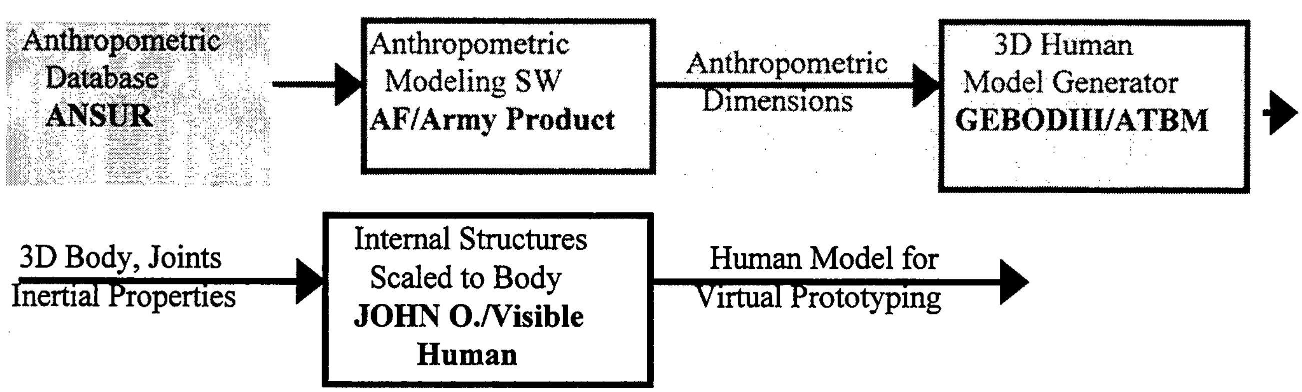

Figure 7. Roadmap for Human Body Data Processing to Produce an Input for Virtual Prototyping

software in **bold** are potential resources available now which can be adopted or modified for the Virtual Prototyping effort.

3.2 Generating the Human Body Model for Virtual Prototyping

The pathway for generating the human body model is linear with data being added, processed, then the results added to the next step. The process begins with a military anthropometric database from which a data set is generated with dimensions equal to those of the desired human model. Those dimensions, together with information on 3D body surfaces, joints, and body segment inertial properties are then used to produce a 3D body model that is a segmented, jointed shell. The internal geometries data, organs, tissues, and fluids, is added and the shell segments size/shape are used to re-scale the internal structures database to fit appropriately inside the body model. The final data set is then formatted for the human model software module in the virtual prototyping software package.

3.2.1 Anthropometric Database.

The size and shape distributions of personnel in the armed forces are represented by measurement surveys. Until recently, the only technologies for obtaining measurements were calipers and tapes. Thus, the data is composed almost exclusively of linear measurements – such as lengths, widths, and circumferences. The principal large surveys are of Air Force flying personnel (1968) and Army personnel (1988). The Army Anthropometric Survey (ANSUR) is the largest and most comprehensive anthropometric survey ever carried out, and was designed to oversample categories of personnel so that future changes in gender, age, and ethnic makeup of the Army could be factored in to update a statistical profile of Army size and shape distribution.[31] Since its publication, other services have carried out so-called mini-surveys which were then matched to ANSUR in order to re-sample ANSUR for statistical analyses. The Natick Anthropology Team maintains a Working Database of ANSUR, which can be accessed by others for statistical analysis.

Although the only current large anthropometric databases are composed of linear measurements, the Natick Anthropology Team and the Air Force Armstrong Laboratory have recently acquired whole body 3D laser scanners manufactured by Cyberware Laboratory (Figure 8). The Army scanner is being used both for special applications projects at Natick and for a larger scale project sponsored by the Defense Logistics Agency's Apparel Research Network. This latter project will result in the scanning of a large number of Army personnel over the next several years. The resulting database will be available for new analyses of true 3D anthropometry. For virtual prototyping, the database will be invaluable in generating state-of-the-art biofidelic human models.

Figure 9 shows an image of a 3D model generated using the Cyberware system using the subject and equipment shown in Figure 8. The scanner records surface color as well as surface points at 3 mm resolution. The light gray lines (right leg, waist, chest, and bicep) are measurements taken off of the 3D data using software also purchased by the Natick Anthropology Team.[32]

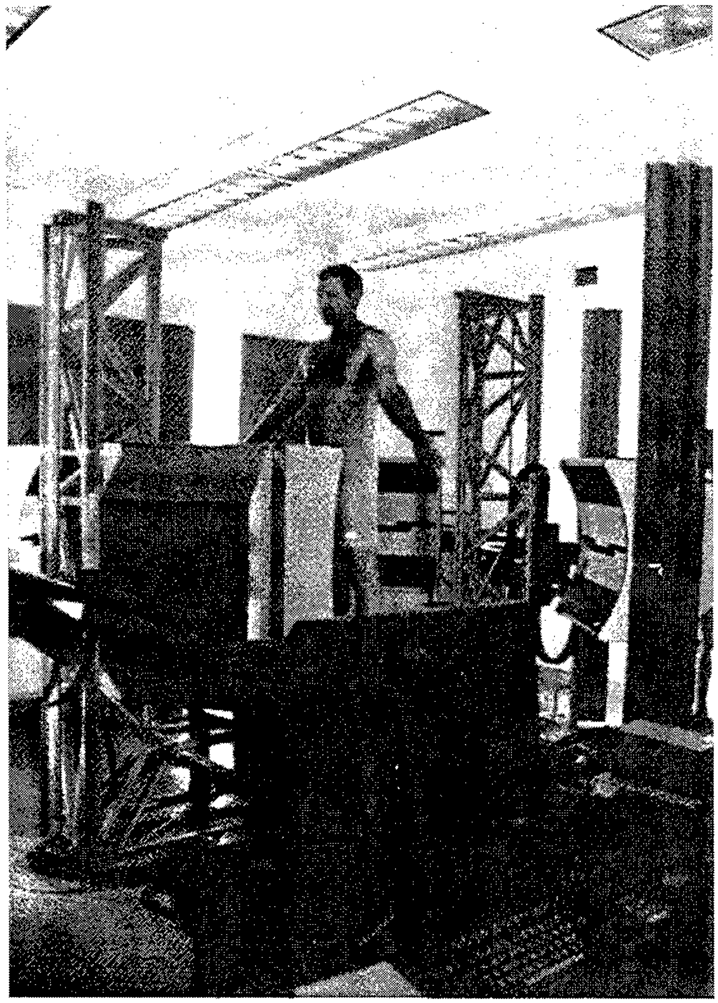

Figure 8. Subject Being Recorded on the Natick Whole Body Laser Scanner (courtesy of Brian Corner of Natick)

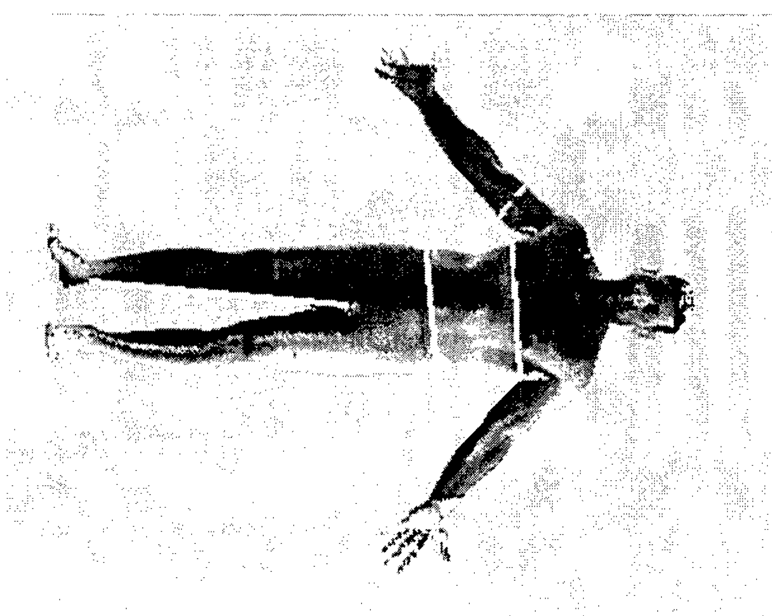

Figure 9. 3D Model from Laser Scan of Subject in Previous Figure

3.2.2 Anthropometric Modeling Software.

In developing human models for virtual prototyping, two factors are important. First, each model has to be realistic, or biofidelic. That is, it must have the size/shape of what could be a real person. Second, the set of human models used in any prototyping effort must encompass some predetermined ranges of size and shape within the population. This range is necessary so that the product being prototyped can be said to accommodate some certain percent of the population – usually 90-95%. For many years, anthropometric models were statistically generated to represent a percentile of the distribution of size and shape in the population. Thus, there were often anthropometric data sets said to represent 5th, 50th, and 95th percentile individuals. These data sets were generated using regression equations predicting all anthropometry from a few dimensions at those percentiles - typically stature, weight, and sitting height. The assumption was that this then would result in the accommodation of all personnel between the percentile extremes (here 90%). The problem is that this assumes that there is a linear distribution of size and shape – something that is not true.

This problem began to be addressed about ten years ago by Gregor Zehner of the USAF Armstrong Laboratory in an effort to develop accommodation models for Air Force cockpit crew station design. Working with Richard Meindl of Kent State University, they developed adapted multivariate statistical techniques based on principal components analysis to generate representative anthropometric data sets which accommodated the non-linear size and shape distribution of flying personnel.[33]

Using traditional regression analyses, the user determines which variable, such as stature or sitting height, is most important, and uses that variable to predict the remaining anthropometric dimensions. In principal components, the first step analysis determines which variables, or dimensions in this case, account for most of the variability in the population. Those variables are then used to predict the remaining dimensions in a range of anthropometric data sets, which can truly accommodate a specified percentage of the population.

This modeling technique is being generalized in a software package called the Multivariate Accommodation Module (MAM), which is also being evaluated by Brian Corner at Natick. When completed, the MAM will be useful in generating anthropometry from the large surveys. At Natick, Dr. Brian Corner and Dr. Claire Gordon of Natick are applying these techniques for *Land Warrior* projects involving helmets, load bearing systems, and modular body armor.

For applications of virtual prototyping, the MAM software or some variant will input anthropometry from the ANSUR Working Database, representing the current population of US Army soldiers, and output anthropometric data sets with the dimensions needed by the next step in the virtual prototyping process – the 3D Human Body Model Generator. The size and shape ranges of the output data sets will be determined by the user. Thus, in order to accommodate, say, 95% of the population, rather than having three data sets – small, medium, and large – there might be ten sets representing extremes and middles along several principal components.

3.2.3 3D Human Body Model Generator

The final 3D human body model for virtual prototyping will run under a current or successor version of *JOHN O.* The internal body geometry for *JOHN O.* is currently described by about 80,000 voxels with tissue properties, while the surface is a series of slices configured from ellipsoids. The body is segmented with joints and can be positioned interactively for use in trauma simulations. The data structures for *JOHN O.* are not identical to the Articulated Total Body Model (ATBM), but they are similar enough that the software used to generate the body geometry for the ATBM can be adapted for the *JOHN O.* virtual prototyping tool. This data generating software is GEBODIII (Generator of BODy data).

GEBODIII was written by Mary Gross of Beecher Research under contract with the USAF Armstrong Laboratory. It is the only program of its kind to use true 3D human body data – surface geometry, segment inertial properties, and joint locations and constraints – to produce anthropometrically accurate human body models for simulations. The writing of GEBODIII followed several years of research and applications into the uses and modeling of 3D data. The data, which was incorporated into the program, was previously used for set-piece applications such as the design of new USAF crash test mannequins (ADAM). The output was tested by not only measuring the anthropometry, but also putting the body model into action to see if the joints and body proportions and shapes were realistic.

The 3D geometry, joint locations, and inertial properties for GEBODIII were largely based on the program FRNKNSTN, also written by Beecher, which was a static 3D human model. FRNKNSTN inputs full-body surface stereophotogrammetric data sets of men and women, computes joint locations based on surface landmarks, and has the capability to move the subjects either interactively, or through a batch movement file. The data sets also contain inertial properties for the body segments so that whole-body properties, such as center of gravity, can be calculated in any position.

Linking together MAM as anthropometric modeling software and GEBODIII (or a successor) as part of a 3D body model generator is an effort now being undertaken at Armstrong. In addition to the input used by the ATBM, whole body laser scans will also be incorporated and high-resolution body surfaces will be produced. These products will be well-positioned to be used or adapted by the virtual prototyping effort as part of the program to generate a 3D human model for *JOHN O.*

3.2.4 Anatomical Modeling

The internal anatomy for *JOHN O.* is based on cross-sectional drawings published early in this century[34] from fifty different supine cadavers and digitized. In stacking the various cross-sections in the digital model, various approximations were necessarily made to achieve alignment and correct posture in a standing position. The level of detail is less than can be obtained from current sources however. The National Library of Medicine's Visible Human Project (VH) has published one full-body male data set and is about to publish a female set. The detail of the data is unprecedented. After being fresh-frozen, the male cadaver was CT scanned and sectioned horizontally in 1 mm thick slices, with each slice photographed at 0.33 mm resolution. The result is a digital data set with 24 bit RGB color, and 0.53 mm CT resolution. The data set is also unprecedentedly large – 15 gigabytes.

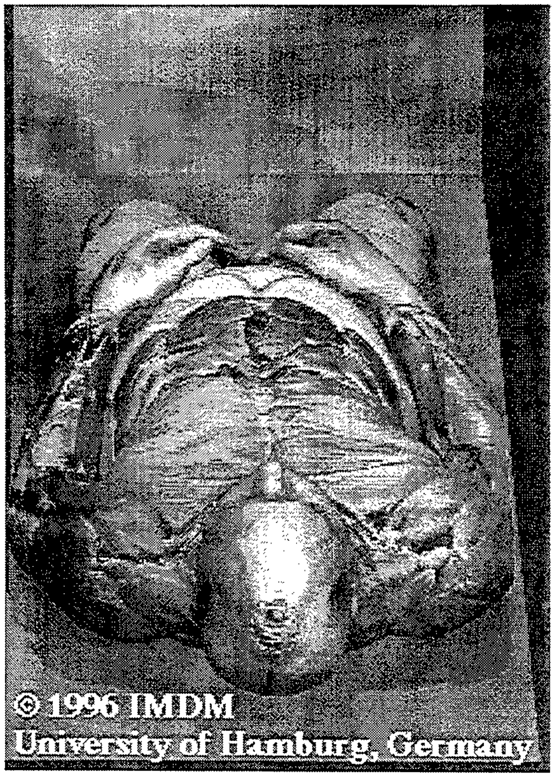

Figure 10. Visible Human Data on the Male Torso Modeled in the VOXEL MAN Software.

While the body is recorded in great detail, the individual tissues and organs are not separated, or segmented, from each other in the raw data. Segmentation is a major hurdle to the efficient use of medical imaging data because it cannot be performed automatically. That is, there is no software which can input a CT or VH data set of, say, the abdomen, and extract, automatically, only those voxels which represent the pancreas. Software that performs segmentation requires significant user interaction.

Fortunately, several organizations are working to produce segmented versions of the VH data. The University of Hamburg (Germany) has a long record of converting medical images to graphics and 3D visualizing. Their current project, VOXEL-MAN is a human model initially based on CT imaging data, but which is now incorporating the VH data.[35] This model is a high-resolution segmented data set with browsing software allowing the user to "slice-and-dice" the data in order to view it from any perspective and at any depth. The segmentation is detailed and includes labels for major structures (see Figures 10, 11 and 12). For the virtual prototyping effort, the importance of this work is that it is available, uses the most advanced data, and it can be adapted to output data for *JOHN O.*

Currently, VOXEL-MAN is available commercially (Springer-Verlag) as an electronic atlas for the head and neck regions. The remainder of the body using Visible Human data is in preparation. A search on-line has not discovered any other sources for segmented VH data sets. The virtual prototyping work could incorporate this data as it became available in useful formats.

To incorporate this information, the internal geometry data must first be re-scaled and reshaped to fit inside the body surface and aligned with the segments and joints specified by the Human Body Model Generator described previously. This is not just a matter of pushing, pulling, and distorting the data so that it fits inside. While tissues such as connective tissue, fat, and parts of the intestines are malleable, many organs do not vary much in size regardless of the shape of the body segment in which they are contained.

Two kinds of information are useful here. First are the clinical anatomical descriptions in most anatomy texts, which localize many major organs with respect to surface landmarks or palpable bony features.

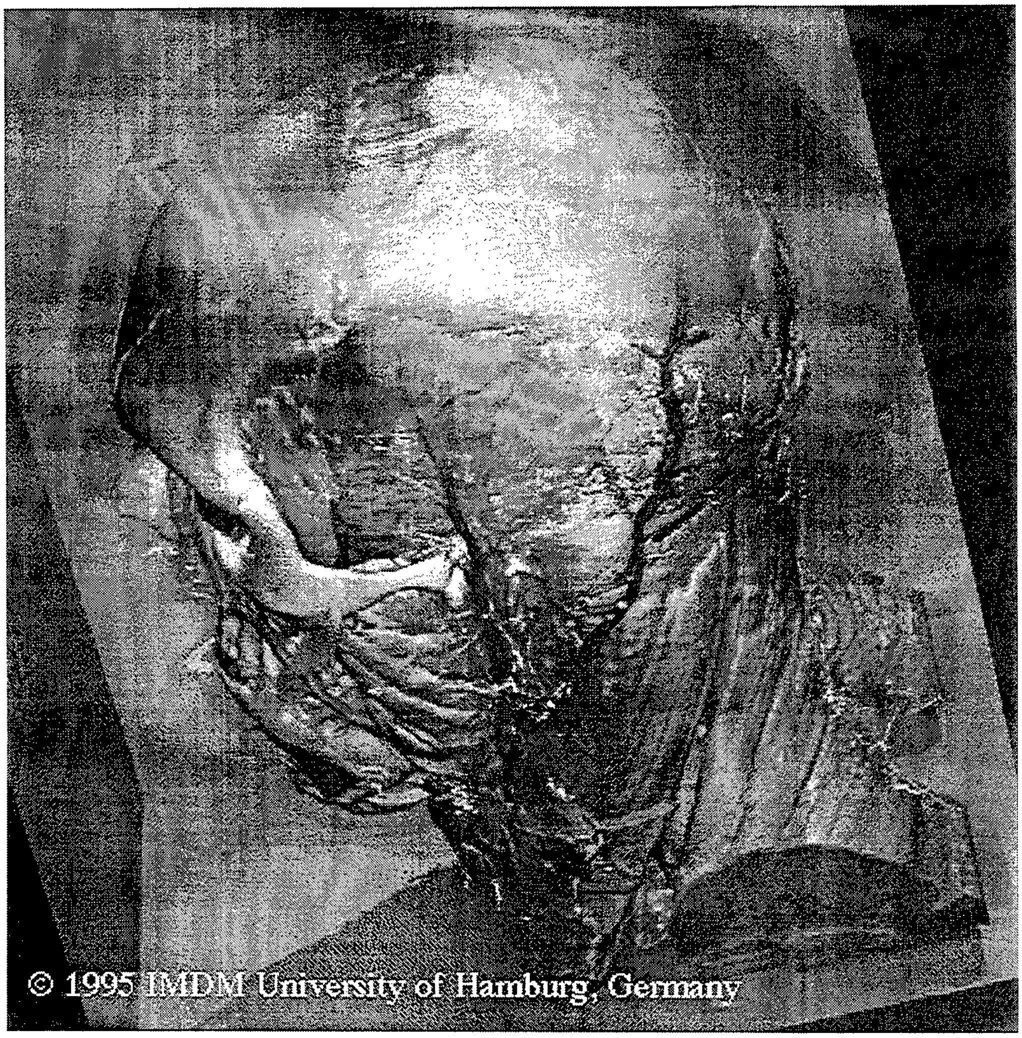

Figure 11. Visible Human Male Head Data Viewed in the VOXEL MAN Software

The second is data on the variability of organ size and weight. Clinical descriptions instruct physicians where to locate various organs under the body surface. These descriptions relate organs to bony features, such as rib numbers, which locate the upper and lower range for where the heart "projects" onto the front of the chest.

The surface features and landmarks necessary to register the internal anatomy can best come from the high-resolution laser digitized subjects which will be recorded and analyzed on Cyberware whole body scanners, such as the one located with the Anthropology Team at Natick.

Figure 12. Visible Human Data of the Abdomen Modeled Using the VOXEL MAN Software

3.3 Protective Equipment and Garment Modeling

As in any computer modeling effort, the more complex the model, the environment, and/or the analysis, the more intensive the computing. In modeling protective equipment and garments on human body models, this is especially true. While much of the solid, physical world, such as machines, have physical characteristics and actions which are well understood and expressed mathematically, garments and personal protective equipment are not only physically complex, but must be prototyped in very complex scenarios. Fabric and fabric-like materials are very difficult to model because of the dynamic properties of folding, draping, and stretching. How these characteristics, especially involving protective equipment, affect the mobility of human wearers is also complex and has not been well measured or understood.[36]

In developing a virtual prototyping model, these materials may be simplified for some purposes, such as near-real time modeling, but left in more realistic, complex models for off-line modeling over longer periods. In addition to the complications of modeling fabric materials, modeling how soldiers work under conditions of load is also complex. The experiences of Gregory Zehner of the US Air Force Armstrong Laboratory in evaluating cockpit accommodation is that encumbering subjects with restraints, clothing, and protective equipment causes them to work to overcome restraints in ways that are not always predictable from the subjects' size, gender, and/or shape.[37] Virtual prototyping models will require substantial validation studies to demonstrate the accuracy of modeling soldiers performing under loads.

Nevertheless, static modeling of protective equipment fit and coverage is underway at Natick using a whole body laser digitizer to record body armor and subjects for analysis of coverage. This work will provide a solid basis for the more complex dynamic modeling efforts needed for full-scale virtual prototyping efforts.

Protective equipment of all sorts can be modeled from CAD files, design specifications, and 3D laser scans. In virtual prototyping, these prototype models are really part of the environment with which *JOHN O.* interacts.

3.4 Virtual Prototyping Applications

1. Military
    a. Evaluating personal protective equipment.
    b. Developing/evaluating protective environments (such as armored vehicles).
    c. Evaluating protective capabilities in different battle scenarios.
2. Other Government
    a. Modeling workplace/home safety and health conditions.
    b. Modeling hazardous government occupations such as police, firefighters, forest fire fighters, and hazardous materials cleanups.
3. Non-Government
    a. Design/evaluation of potentially hazardous workplace processes.
    b. Modeling accidents in litigation.

4. TRAUMA MODELING

This section is on trauma modeling and is divided into two sections. Section 4.1 gives an overview of MRC's approach to improving analysis of penetrating wounds and is an outgrowth of trauma models developed in the DARPA/MRDC/MRC *Simulation and Assessment of Musculoskeletal Trauma due to Missile Penetration* program. Section 4.2 describes MRC's approach to modeling human response to blunt trauma from non-penetrating projectiles.

4.1 Penetrating Wounds

In the DARPA/MRDC/MRC *Simulation and Assessment of Musculoskeletal Trauma due to Missile Penetration* program, trauma models are being developed which describe tissue damage due to penetrating wounds of the lower extremities. These models are being implemented in a *virtual reality* surgical simulator and employ biomechanical assessment algorithms to describe degraded physical abilities resulting from the wounds.[38]

Of perhaps most significance for this report, this program developed a semi-analytical methodology that explicitly describes the forces promoted by the interaction of a projectile with biosimulants and human tissue. The biosimulant targets consisted of different formulations of ordnance gelatin. It was assumed in conducting these experiments that the gelatin manifested similar phenomenology to human soft tissue upon ballistic impact. It was not assumed, however, that there was any obvious quantitative relation between projectile penetration in the gelatin targets and humans.

The models were developed by performing ballistic experiments in biosimulants using spherical projectiles. The mechanical properties of the biosimulant were parametrically varied to determine the effect on projectile terminal ballistics. By observing the velocity profile of the spherical projectile as it penetrated the gelatin target, an explicit determination of the retarding force per unit projectile mass could be determined as a function of target mechanical properties. The resulting model was formulated in terms of parameters that could be derived from existing mechanical property data available for fresh unembalmed cadavers.

These properties consist of quasistatic strength and modulus data, which are applicable to projectiles penetrating at very slow velocities. In this regime, tissue behaves like a viscoplastic solid. At high penetration velocities the mode of projectile-tissue interaction is primarily fluid mechanical where tissue densities and drag coefficients are relevant.

The material model describes projectile velocity as a function of penetration depth using the asymptotic behavior at very low and high velocities, where relevant mechanical properties can be obtained for human tissue, to construct similar properties in the intermediate velocity regime. In the intermediate regime, tissue behaves as a multiphase medium with solid and fluid contributions. This applies to ordnance gelatin and human tissue.

It is in this intermediate regime, where mechanical properties cannot be explicitly determined and that general purpose finite element codes go awry. Mathematically, the slopes of two asymptotes described earlier can be matched to describe the retarding force per unit mass for a spherical projectile in this regime. A mathematically rigorous derivation of this approach is presented and published in the *Werner Goldsmith Symposium* on Impact Phenomena.[39]

More complicated projectiles are modeled as an ensemble of spheres where the retarding force per unit mass for each sphere in the ensemble is scaled from the appropriate spherical penetration data. The retarding forces for each sphere is then integrated over the surface of the ensemble to obtain lift and drag forces.[40] An example of a computer simulated trajectory involving a 19.6 grain flechette fired into a 30 x 30 x 60 cm block of 20% ordnance gelatin is shown in Figure 13. A comparison between the predicted velocity profile as a function of penetration depth and a ballistic experiment using orthogonal arrays of flash x-ray heads is shown in Figure 14.[41] The agreement between predicted and experimentally determined values is seen to be very favorable. This type of predictive model correlation with experiments in a target medium with unknowns and phenomenology similar to human tissue instills some confidence in the modeling approach. Since the model has been formulated in terms of parameters that can be physically interpreted, human tissue properties corresponding to these parameters can be substituted into the model to describe tissue response in humans. Validation of this methodological step is being accomplished as part of the DARPA/MRC program by selecting specific cases from the WDMET database where actual wounds will be simulated and correlated with the corresponding autopsy data.

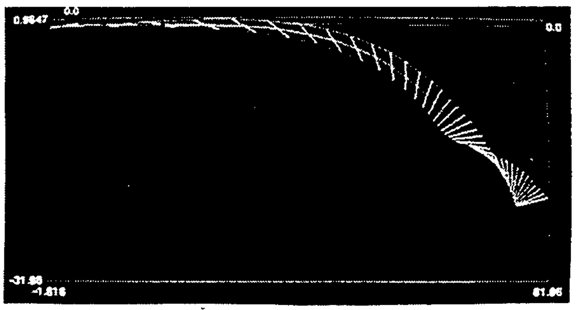

Figure 13. Computer Simulated Trajectory of 19.6 grain flechette fired into 30 by 60 cm 20% ordnance gelatin block at 1200 fps with 6.6 degree yaw

Source: Natick/MRC DAAK60-C-92-0003

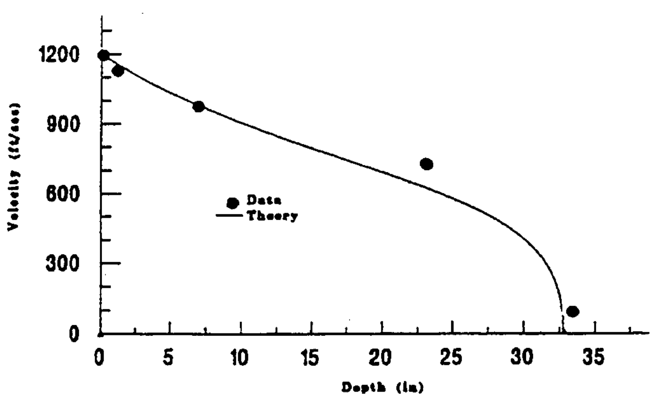

Figure 14. Comparison between Predicted Results and Ballistic Data for Flechette with a Striking Velocity of 1200 fps and a Yaw of 6.6 Degrees

Source: Natick/MRC DAAK60-C-92-0003

4.2 Blunt Trauma

Projectiles that strike the human body but do not result in a penetrating wound can still produce injuries, which range from minor abrasions and contusions to serious trauma such as organ rupture and skull fracture. The regions most vulnerable to blunt trauma injury are the friable organs of the abdomen (liver, spleen and kidney) followed by the head, and heart.

Little is known concerning the relationship between the occurrence of blunt trauma injury, striking location on the human body, impact conditions, target and projectile properties. There have been a variety of phenomenological criteria proposed over the last three decades. These criteria have been appealing because the resulting "lumped parameters" have been easy to apply, particularly for system studies. However, these criteria remain largely unsubstantiated and are only useful in lieu of more rigorous criteria, which currently do not exist.

The sequence of events promoted by a non-penetrating projectile can be thought of in terms of Figure 15. The impact promotes a highly localized, time varying, compressive pulse on the target surface. The amplitude of this pressure distribution is determined by the projectile striking velocity and mechanical impedance mismatch at the target and projectile interface. The length of this initial compressive pulse is determined by the geometry of the contact surface between the target and projectile and the length of time required for a sufficiently large tensile pulse to be reflected from an interface, in the projectile or target, to the impact region. When the contact surface, which was initially in compression, is subject to tension, the projectile and target separate and no stress or momentum is transferred. This behavior is complicated by the highly non-linear nature of the problem. That is, the geometry of the contact surface will change during the contact time and the mechanical impedance of materials affected will change as a function of stress according to their respective equations-of-state.

The pressure developed on the target surface will radiate through the body at characteristic wave velocities and attenuate with propagation distance due to geometric scattering and dispersion. Waves will also be reflected, diffracted, and transmitted at tissue boundaries leading to highly non-uniform pressure distributions as the waves propagate.

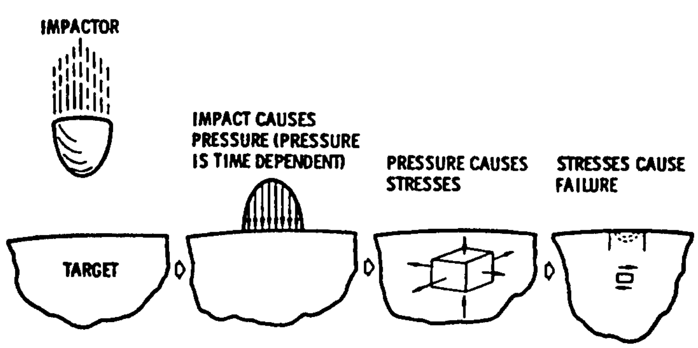

Figure 15. Pressures Promoted on the Impact Surface by the Impact Propagate though the Body

As the stress waves interact with intervening tissue, if the duration of the incident wave is sufficient for the tissue to respond, tissue will be displaced. This could lead to high strains and tearing of tissue. If the tissue does not have time to respond, high stresses will be promoted in the tissue. If these stresses exceed the ultimate mechanical properties of the affected tissue (which is a function of

the rate at which strains are applied), the high stress could initiate damage or in brittle tissue, fractures. Normally, this would be predicted by comparing the amplitudes and duration of the stresses and strains promoted in the vicinity of affected tissue with strain rate dependent ultimate mechanical tissue properties.

The problem with developing a predictive methodology that describes the phenomenology above is at least threefold. First, spatially and temporally resolved descriptions of the *forcing function* or initial pressure distribution promoted by a non-penetrating projectile striking the human body is not known. This forcing function will vary over the surface of the human body with the compliance of the impact location. Until this forcing function is adequately described, subsequent analysis is hypothetical.

The second obstacle concerns the lack of *in vivo* dynamic tissue properties. This, for example, thwarts the application of general purpose finite element codes. Although the mathematical techniques associated with these codes are elegant, without the appropriate ***dynamic*** tissue properties (which in general cannot be obtained), many assumptions and idealizations must be made to supplant the lack of relevant material properties. This problem is exacerbated by not having an accurate description of the forcing function applied to the ensuing model. Further, without any means to verify code predictions; the application of these codes to the various problems being discussed is highly speculative.

The final obstacle concerns a lack of insight concerning the damage response modes being analyzed. In general, a technique such as finite element analysis is not useful for predicting the occurrence of damage without some insight as to what type of damage is expected and where it is likely to occur. The initiation of damage is often accompanied by singular stress fields (stress fields which become infinite or go to very high values over short distances). In general, these fields cannot be spatially resolved by analytical techniques that employ numerical discretization schemes such as finite difference or finite element techniques. Results from these types of codes, however, can be used as boundary conditions for continuum solutions. These solutions can be used to analyze stress and strain fields in the immediate neighborhood of the damage. In order to apply these techniques considerable insight must be employed however as to where the damage is likely to occur, what type of damage-response mode is invoked, and how intervening material should be discretized. Different forcing functions and damage-response modes often entail different discretization schemes and damage criteria. The application of any general purpose numerical technique therefore requires at least four things: (1) A description of the forcing function, (2) Insight as to where damage is likely to occur and damage-response-mode promoted, (3) *In vivo* dynamic properties of affected tissues, and (4) Convergence studies on the numerical grid.[42,43,44,45,46,47,48]

The convergence studies alluded to in item 4 refers to ensuring that for the same problem, different numerical grids yield the same solution. Following convergence studies or especially if the solutions resulting from the various numerical grids do not agree (which they probably will not), the various solutions must be compared to experiments and/or simplified problems that can be solved by alternative methods. The simplified problems chosen should confront similar forcing functions and damage-response-modes but employ simpler geometries than the problem of interest.

The work flow suggested for investigating blunt trauma problems is shown in Figure 16 and systematically addresses many of this issues described previously. The analysis consists of four technical tasks: (1) The conduct of ballistic experiments, (2) Analytical Development, (3) Clinical data collection and analysis, and (4) Development of injury thresholds.

4.2.1 Ballistic Experiments

With reference to Figure 16, experimental data should be collected relative to the pressure time histories generated at the front surface and in depth, of a target subject to ballistic impact of selected Non-Penetrating Kinetic Energy (NP/KE) projectiles. The target surrogate should mimic the dynamic stiffness of various anatomical regions of the human body. A special target can be developed employing custom made microstress gages in a layered configuration. The experiments can be repeated with various clothing options, striking obliquities, and striking velocities. Impact surface, pressure histories for projectiles tested as a function of striking conditions, clothing, and striking obliquity can be determined from this effort.

Experimentally determined pressure time histories on the impact surface are needed for three reasons. First, they are equivalent to the loads on a structural model and are required as input to a modeling scheme in order to determine mechanical response. Second, characteristics of the incident pulse, as revealed in these experiments will identify the type of mechanical response evoked by the NP/KE interaction with the body. This may include either a quasistatic (crushing), viscous, stress wave, and/or shock type of response. Each of these response modes requires very different and to some extent, mutually exclusive, modeling strategies. Finally, the characteristics of the incident pulse will also determine the overall size and how finely detailed the mechanical model must be.

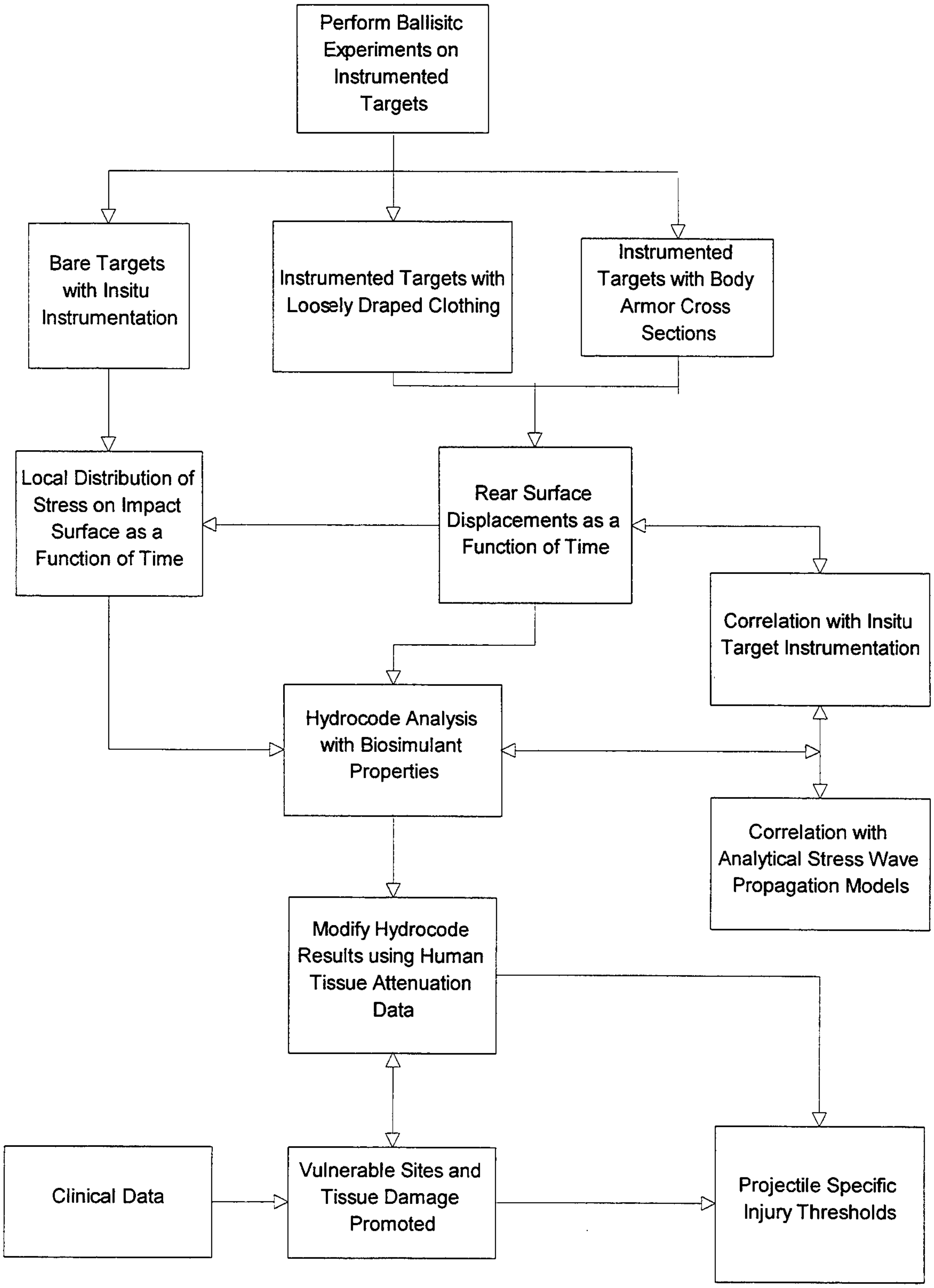

Figure 16. Work Flow

4.2.2 Clinical data collection and reduction

The purpose of this effort would be to identify tissue susceptibilities to the effects of NP/KE projectiles. Unfortunately, clinical data that is directly relevant to the effects of NP/KE projectiles on the human body is limited. While we will acquire data relative to the use of rubber and plastic bullets by the British for crowd control in Northern Ireland, and the limited data available in the WDMET database for lethal projectiles that were defeated by body armor and produced blunt trauma injuries; a more comprehensive strategy is required. The more comprehensive strategy for identifying and quantifying tissue susceptibilities of interest is threefold.

First, existing trauma databases will be *mined* to extract information relative to the pressures, stress, and strains, which cause tissue damage from forcing functions similar to those demonstrated at the impact surface during the ballistic testing. It is not the source of the pressure distribution on the target surface that is important (that is, it is not important whether the pressure distribution was produced by a NP/KE projectile, a car crash, sports injury, or fall). Rather, it is the amplitude, spatial and temporal distribution, and location of the pressure distribution on the human body that leads to ensuing tissue damage. Therefore, databases that incorporate medical information relative to other sources of trauma can be exploited provided that the data is reduced in terms of the forcing function causing the damage (as opposed to the source of the damage).

Second, using the data above, susceptible anatomical structures and response modes will be identified. This would be done in terms of anatomically specific forcing functions determined during the ballistic testing.

Finally, data from the two subtasks can be reduced in terms of a common set of parameters. This effort will serve to focus modeling activities on only those structures and response modes that might be affected by a NP/KE projectiles. The output of this effort will be identification of: (1) Susceptible tissues and anatomical structures, (2) Damage-response modes promoted by the impact, and, (3) Deleterious levels of response and symptomatic manifestation along with supporting rationale and references.

4.2.3 Analytical Development

Based on the susceptible anatomical structures and response modes identified previously and the forcing functions derived from the ballistic testing, analytical models can be developed to determine levels of response promoted by the NP/KE projectile interaction in susceptible anatomical structures.

Analytically predicted levels of response could be correlated with deleterious response thresholds documented in selected cases from the trauma databases *mined* earlier. Biosimulant targets with implanted instrumentation can be configured and layered to represent susceptible anatomical features and structures. These targets would be fabricated with materials that bound or represent variations of tissue mechanical properties. In-situ pressure transducers can be used along with temporally correlated in-situ photography. Measured pressure time histories, photographically recorded displacements, and posttest damage could be correlated with analytical models that are developed.

4.2.4 Injury Thresholds

The models and data from the previous efforts described could then be exercised to describe human thresholds and response. Damage envelopes (with uncertainties) as a function of range and striking location on the body can be rendered for NP/KE projectiles considered. Vulnerability envelopes for humans as a function of projectile type, clothing, and range can also be determined.

The effort described in this section would determine injury thresholds as function of relevant parameters associated with interaction of non-penetrating projectiles and human targets. The proposed effort could also use the information developed on injury threshold to investigate performance specifications for body armor. Current performance specifications for body armor relative to blunt trauma have been very successful in mitigating blunt trauma injuries. In fact, we are not aware of any cases in the civilian arena where a serious blunt trauma injury was sustained by a police officer while wearing the appropriate class of body armor. In the case of the military, which is confronted by a very different array of threats, however, this does not seem to be the case.[49,50] The question however is whether current blunt trauma specifications might actually be too conservative in general or even correctly specified for the military. Relaxing this specification would reduce physical encumbrances and enable body armor to be more flexible. This would make it easier to extend coverage areas, particularly for police officers, military police, and soldiers in armored vehicles who require a lot of torso flexibility.

4.2.5 Related MRC Efforts

In addition to the DARPA/MRC effort concerning penetrating wounds discussed in Section 4.1 there are two additional currently funded DoD efforts at MRC that are directly relevant to the proposed work. Contributions of these programs to the proposed effort are described next.

Integrated Ballistic Casualty Reduction and Ballistic Protection Model and Development of a Soldier Protective Ensemble Computer Aided Design System

(Natick Research Development and Engineering Center Phase I and II SBIRs). This effort is developing a computer aided design system to assess the casualty reduction potential of body armor designs impinged by munition fragments, small arms fire, and blast effects. Injuries considered include penetrating wounds, blunt trauma, and blast wave effects on the thoracic and abdominal cavities.

Models have been developed for the SPE/CAD system which describe displacement history, strain, and projectile velocity as a function of penetration depth through body armor. Rear surface body armor displacement histories are correlated with ballistic experiments in Figure 17.[51] These displacement histories can be used directly as initial conditions in a hyrdocode or viscous-dashpot model to describe visceral response and the occurrence of blunt trauma injury. These data can also be used to determine chest or abdominal wall displacement velocity and compression for direct application into phenomenological criteria such as the Viano viscous criteria.[52,53] Photographs of the body armor interface corresponding to the data points in Figure 17 are shown in Figure 18. Figure 19 shows the same ballistic experiment without Gelatin backing.

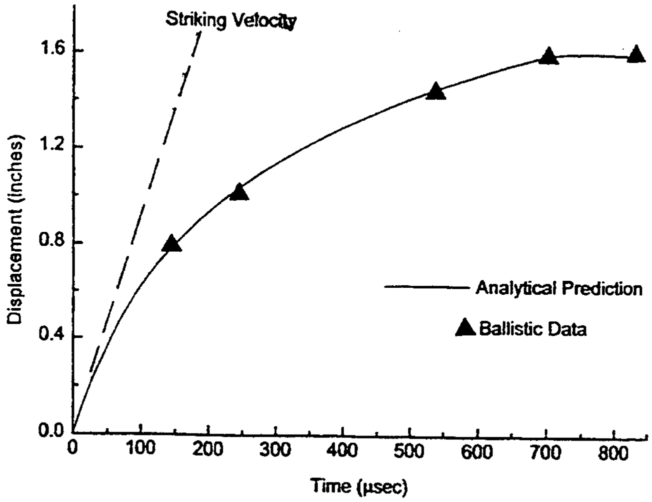

Figure 17. Comparison of Predicted versus Observed Rear Surface Displacement History for Impact of .38 Special Bullet Striking 6 Layers of 1500 Denier Kevlar-29 Fabric against 20% Ordnance Gelatin

For situations where projectile perforation of the fabric assembly is imminent, fabric deformation is severe with extremely high curvatures associated with fabric strains exceeding ultimate values. The fabric can be seen in many cases to wrap around the projectile body. This forms a "nipple" in the fabric, which is superimposed on the larger scale rear surface deformation.

A gelatin backing suppresses this nipple formation and reduces fabric strain. During later phases of the projectile-fabric interaction, retarding forces in the gelatin, as shown in Figure 20, exceed the retarding forces provided by the Kevlar fabric. For gelatin backed fabric, at late time, the stress waves promoted in the fabric by impact envelope more fabric material reducing local curvatures at the projectile fabric interface. This reduces the force component of the fabric in the direction of the projectile velocity vector.

0.14 msec
0.8 inches

0.24 msec
1.0 inch

0.54 msec
1.4 inches

0.712 msec
1.6 inches

0.840 ms
1.6 inches

Figure 18. Rear Surface Deformation of 6-Layer, 1500 Denier, 2 x 2 Basket Weave Kevlar-29 Fabric Loosely Draped over 20% Ordnance Gelatin Block Subject to Non-Perforating Impact by .38 Special Bullet (130-gra in FMJ Hemispherically Blunt Cylinder) with Striking Velocity of 800 fps

Source: Natick/MRC contract DAAK60-C-92-0008

0.240 msec
1.2 inches

0.80 msec
2.2 inches

0.8+ msec
Bullet is at 5.4
Bullet Residual Velocity = 580
Fabric is Displaced 1.1

Figure 19. Rear Surface Deformation of 6-Layer, 1500 Denier, 2 x 2 Basket Weave Kevlar-29 Fabric without Ballistic Backing Material Subject to a Perforating Impact of a .38 Special FMJ Bullet

Source: Natick/MRC contract DAAK60-C-92-0008

DLA/DARPA/NaRD/MRC Senate Liner Development for Combat Casualty Care. This effort will deliver a "breadboard design" and "bench top" demonstration of the sensor configuration, data acquisition system, analytical models, and signal processing algorithms to be incorporated in the Sensate Liner System (SLS). The SLS is being developed to: (1) Detect occurrence of penetrating wounds; (2) Classify the projectile causing the wound; and, (3) Determine projectile entry, exit, and/or resting location in the body.

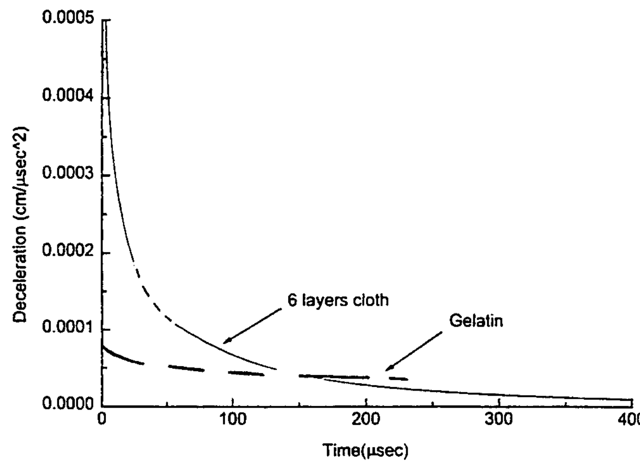

Figure 20. Comparison of Time Resolved Resultant Projectile Retardation Force Developed in Kevlar-29 Fabric and Ordnance Gelatin Backing

Source: Natick/MRC contract DAAK60-C-92-0008

The first objective was addressed by designing an array of overlapping individual piezoelectric film gages, mounted in fish-scale-fashion on a flexible, wearable undergarment. These gages are known to respond to compressive loading, which will be provided by the impacting projectile. Since a design objective was to deliver zero false alarms it was necessary to design the monitoring circuitry to reject all loading not attributed to the penetration process. This was achieved by the use of a short (1 microsecond) response cycle circuit so that all slow loading would be ignored. The penetration event alone is then identified by the fast rising signal that exceeds an adjustable threshold voltage. This event causes the data acquisition system to be activated for real-time data acquisition. Also the physical penetration of the film causes the gage to short out electrically which results in a rapid signal return to zero. The penetrated gage is thus readily identified for both entry and exit event if any. The known location of the gage or gages involved will then localize the penetration event.

The detection/trigger event described above also triggers data acquisition from an array of piezoelectric gauges mounted on the anatomy of the soldier. These gages will record the acoustical signatures produced by the penetrating round, at various locations on the body. Computer algorithms have been developed that will identify characteristic features typical of the penetration, at each of the monitoring gages and calculate the location from which the event originated. This approach will permit the mapping of the wound tract. In addition, power spectral density analyses is performed on the acoustical signatures recorded by each gage. Recognizable features in the spectrogram permit the identification of the type of projectile involved in the penetration process and the extent of the wound cavity. The latter discrimination is based on empirical data. The combination of the measurements and analysis facilitate the automatic quantifying of the wound severity and the assignment of a wound severity code. This code, together with global positioning coordinates, when transmitted to a medical center will permit the timely allocation of medical resources to enhance the survival probability of the wounded.

To complement this system, we are presently investigating the applicability of a microimpulse radar system, developed by Lawrence Livermore National Laboratory. This system which has minimal power requirements has the potential for performing three-dimensional imaging functions that could also locate and size the wound track and the resting residual penetrator.

This effort has developed the targets and insitu instrumentation technology to quantify the stress fields promoted behind body armor by non-penetrating projectiles.

5. SOFTWARE ARCHITECTURE AND ENVIRONMENT

JOHN O. will be immersed into a real time simulation environment to complete the implementation of the virtual prototyping system. One such simulation environment commonly in use in DoD activities is Coryphaeus®. The approach will be similar to that used in the MRC STRICOM Phase II SBIR project (see Section 1.3). In the proposed development effort a hybrid of *Commercial Off-The Shelf* (COTS) and *wrap-around* custom software will be employed. Coryphaeus® is presently the leading candidate for providing the core visualization and real time simulation capabilities. A custom software development effort will be utilized to create the desired capabilities, which are not available in Coryphaeus®. *JOHN O.* will be modified to export all anatomical parameters to the real time simulation portion of the virtual prototyping system. *JOHN O.* will in a sense become the compute server for the entire system.

Several geometric databases will be required for the personal protective equipment virtual prototyping system. The key databases are:

- Human models (various sex, race, and anthropometric categories)
- Personal protective equipment
- Workspace
- Weapons and other equipment
- Environments
- Facial identification and clothing
- Wounds

A user interface will be developed to configure and monitor the virtual prototyping simulation. It will have areas for selecting all items listed above. Since it would be prohibitive to create 3D models for all possible combinations of digital human models, only the most common combinations would be immediately available at runtime. Any "non-standard" digital human will be configured with the interface and information sent to the *JOHN O.* module to build the required geometry. This polygonal geometry will then be loaded into memory for the current session and will then also be added to the list of available human models for future use.

Three-dimensional models of the personal protective equipment will be created either in a CAD package or within the Coryphaeus® modeling environment. If the protective equipment is still under development, the designer can export a model from the CAD tool he/she is using and load it into *Designer's Workbench* for final preparation. Again, once these models have been created the first time they will become part of the library and will be available for future sessions.

A library of vehicles, weapons, and environments will be created much in the same way. Also, since many of the desired vehicles, weapons, and environments have already been created for other DoD and commercial uses, they may only require converting to a new format to be made available for use in a virtual prototyping session.

When two or more characters are immersed, unique identification will be crucial for effective simulations. Thus, a library of "faces" and clothing will be created. The faces will be simple texture maps created from color photographs. Front and side photos will be digitally "stitched" together to create a texture which can be applied to any digital human for unique identification. Various materials and colors will be available for clothing.

An articulating human model will be developed for this effort. This model will allow for articulation within the virtual environment and will be able to simulate the interaction of the individual and the space or vehicle he or she is located in. The model will be able to reflect changes in range of motion due to protective equipment the individual is wearing or due to wounds. There are three aspects to this fully articulating human model:

- 3D geometry, materials, and textures
- XYZ coordinates and rotation constraints for all joints, limbs, and movable parts
- Navigation and manipulation input and feedback links

The geometry will be made of triangular polygons with simple materials and textures. Sufficient polygonal density will exist to ensure adequate representation of the digital phantom. As discussed, the geometry will be created based on sex, race, and anthropometric specifications, selected from a pre-defined list, or acquired from the Natick Cyberware body scanner. Texture maps will be used to add specific faces for individual identification.

The data files describing the digital phantom will contain all data structures required by Coryphaeus®: Three-dimensional coordinates for each vertex, vertex connectivity table for each polygon, axis of rotation and rotation constraints for each movable element, and material, and texture definitions. These files will be created during the setup phase of the simulation.

There are several methods that can be implemented to determine the functionality of a particular piece of protective equipment with respect to the workspace. Pre-programmed operations and movements within a particular workspace combined with collision detection routines to identify interference between components is one option. This option would not require real time visuals but instead could utilize post-processed visualization.

Another option, will be to have multiple "players" immersed in a virtual reality (VR) environment. Each player would wear a motion suit or other positional feedback system to detect displacements limbs and joints. This type of "motion suit" is common in real time motion capture applications. These players would also wear the virtual personal protection equipment and would virtually interact with the workspace. Any lack of mobility would show up as an inability to perform various operations.

There are also several solutions between the multiple player *man-in-the-loop* immersive environment and the non-immersive single player environment. For example, instead of having completely immersed players, we could have one player immersed and interacting with a workspace. In this way, only the parts of the player, that the player can see need be visually represented; arms, hands, legs, and feet. This simplifies the visuals and the VR hardware significantly.

If the "player" sustains some type of injury, the limitation in range of motion or limited use of a limb can easily be integrated into the simulation by limiting the effectiveness of the VR hardware. For example, if the "player" is shot in the left shoulder, and the damage to the shoulder (calculated by *JOHN O.*) would result in a disabled left arm, the "player" would not be able to use the simulated left arm or hand to manipulate any VR device or weapon.

The design of protective equipment as conceived of in this effort has three basic cycles: static design, dynamic design, and field testing. In each of these phases the application of 3D visualization can be used to improve the design process.

5.1 Static Analysis

During static analysis, various factors are evaluated and engineering trade-offs are made. The design of personal protective equipment must balance factors of wearability, durability, cost, and overall effectiveness of protection. Successful completion of the proposed Phase II effort will provide a significant increase in the amount and quality of the data available to the designer. To make effective use of this influx of data, the designer needs improved tools to evaluate the results of trade-offs made during each design iteration. Using 3D modeling and rendering provides the foundation for such a tool set.

The overall effectiveness of personal protective equipment is a balance of the greater encumbrance imposed by the equipment versus the higher probability of mission completion through reduced casualties. Here again, 3D imagery can be used to assist in the design process. This is accomplished by identifying the range of threat environments in which the equipment is to be used, and the distribution of injury severity and type that can be expected in those environments. This is then translated into a visual model indicating areas of the body at greatest risk to different types of injury (i.e., penetrating wounds, blunt trauma, and heat stress). The designer can then interactively apply protective material, in a selective manner, until an acceptable risk level is reached. The designer can thus use a minimum of mass, thereby reducing encumbrance, while still providing the maximum level of protection at a given cost point.

Wearability is a function of several factors such as mass distribution, abrasion, heat, transfer, and flexibility. The 3D image can present the designer with color coded representations of how the proposed equipment interacts with a representative selection of wearers. Given the current and short term analysis capability, the main factors to be evaluated at this stage are protection, range of motion, mass distribution, total weight, and heat transfer. As analytical models of human mobility and range of motion improve, these models can be incorporated into this phase of the analysis as well.

Combining analytical models of mobility and range of motion with material property data will allow the evaluation of protective equipment for durability and potential encumbrances to range of motion. Improved durability can be obtained by identification, as early in the design cycle as possible, of points of high stress or wear. This information permits the designer to select materials and construction techniques with greater value and performance at a lower cost. The implementation of the system will have major components as shown in Figure 21.

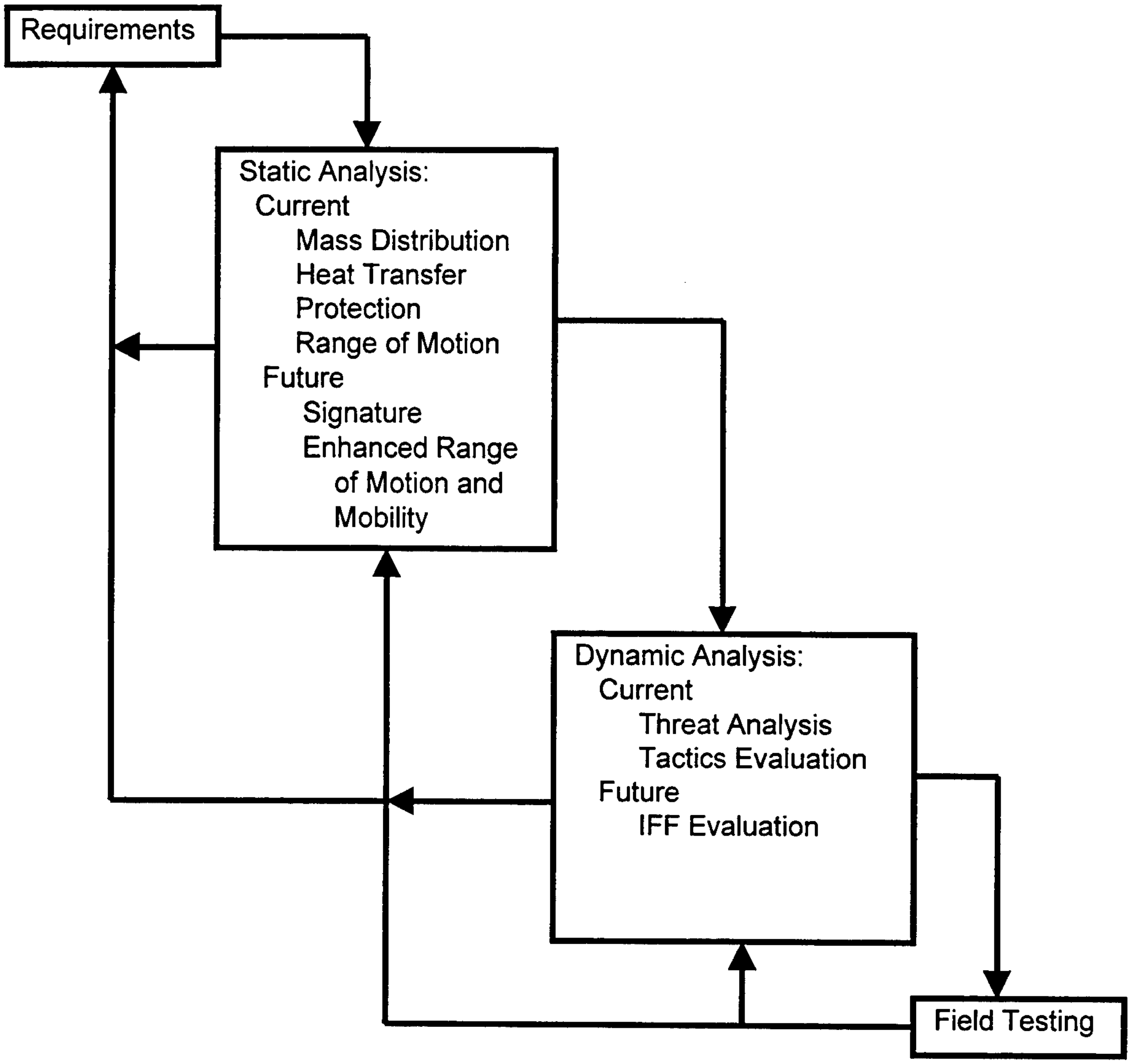

Figure 21. Relationship of Various Analysis Options in Virtual Prototyping System

During the initial design phase, the designer reviews the effect of the projected threat environment. Given a representative selection of unprotected anthropomorphic models, the designer can create a color coded visualization of the projected distribution and severity of different classes of injury. This process can be repeated with the models protected by current issue equipment. As the design matures, the new equipment design is evaluated with respect to the same criteria as applied to the unprotected and currently protected model. The designer can then be presented with a side by side comparison of the effectiveness of the proposed design.

Since the evaluation process is based on a detailed anthropomorphic model, the designer has the option of examining detailed representations of the characteristics of selected wounds. For example, if the general evaluation of the protective equipment to a certain group of

anthropomorphic models indicates a high occurrence of trauma to the lower back, the designer can move into the body and examine the nature and extent of the trauma. This form of evaluation can provide the designer with insight needed for innovative solutions (see Figure 22).

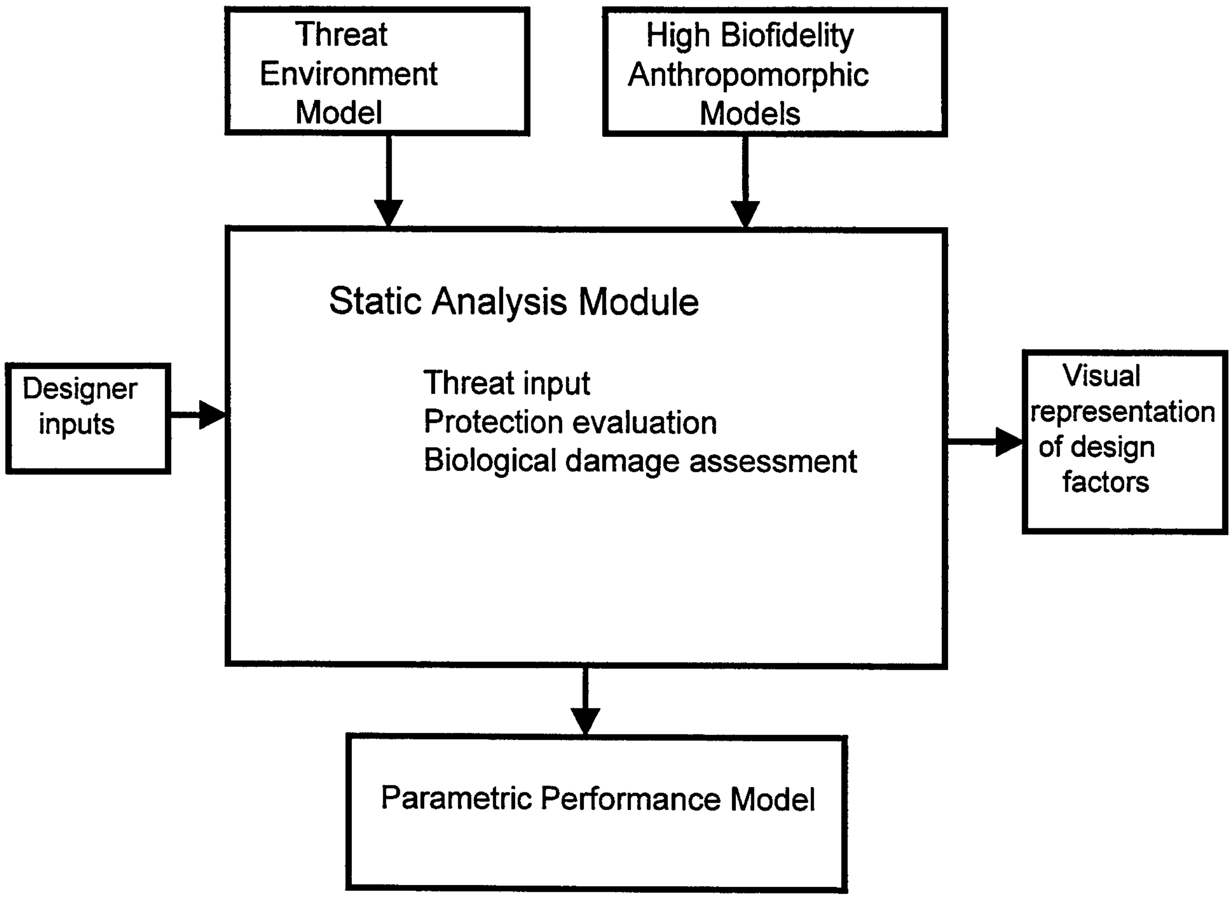

Figure 22. Flow of Information in Static Analysis Module

5.2 Dynamic Analysis

Once a cycle of static design is competed, a dynamic analysis is needed to validate the conclusions of the static analysis (Figure 23). The dynamic analysis looks for such features as significant changes in bulk, which would effect the selection of cover or access to confined spaces. Significant changes to endurance due to better heat transfer or reduced mass, could effect the selection of tactics. The dynamic analysis would take synthetic actors/combatants through a series of scenarios. Each run would be scored against a baseline simulation. The simulation would be controlled by a combination of self-directed characters and a human director who could make use of new tactical opportunities.

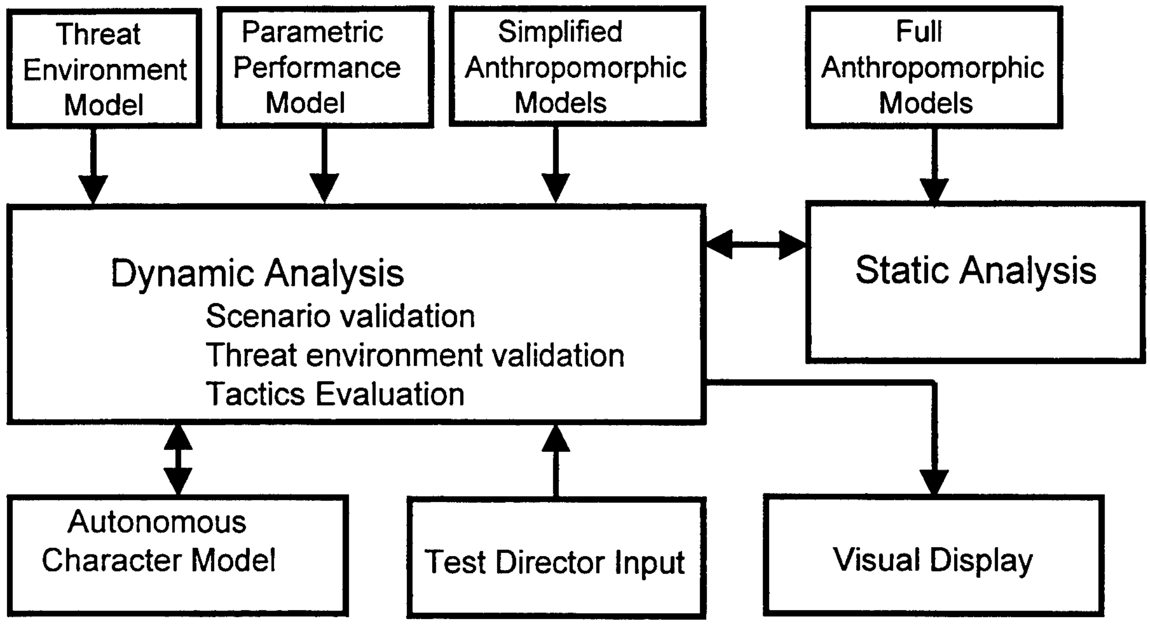

Figure 23. Flow of Information in Dynamic Analysis Module

The parametric model provides a level of abstraction from the high fidelity models used in the static analysis. This makes the parametric model more appropriate for use in dynamic analysis. Yet this does not preclude the use of the static analysis tools during dynamic testing. If at any time the test director wishes to validate an event in the dynamic analysis, the dynamic analysis can be suspended and the desired event run through static analysis to obtain more detailed results.

The static analysis provides the designer with statistical data on the type and distribution of impacts from which the equipment is suppose to protect the wearer. The dynamic analysis will demonstrate that the original threat model is consistent with the manner in which the equipment is used. The results of these tests would be passed back to the static analysis to provide a more complete analysis of the protective equipment.

When the design is approaching the point where prototype equipment is to be built, a virtual environment can be used as a final human factors check of the protective equipment. A virtual environment being developed by MRC under another effort (discussed in Section 1.3) will be compatible with the Natick virtual prototyping system and could be exploited as the intermediate step between theoretical analysis and actual field testing alluded to in Section 5.2.

However, the response of teams using the new equipment can also be evaluated. Given a threat environment, a team using baseline equipment would normally select one of several tactical solutions to resolve the situation. Since no solution to a combat situation is risk free, every solution must be evaluated on a statistical basis, weighing team losses against mission success. By substituting the proposed protective equipment, new tactical options can be evaluated as well as changes to loss rates using conventional tactics.

Once development of the virtual environment and character simulator are sufficiently mature, follow-on activities could include, for example, evaluating visibility and signature issues. Do team members find it easier or harder to identify other team members? What is the perception of equipped team members from the point of view of the aggressors?

An example of this issue would be the effect of a characteristic Infra Red pattern resulting from the heat transfer characteristics of the protective equipment. If only the team members have suitable IR equipment to detect this pattern, the pattern becomes an aid to recognition and reduces losses to friendly fire. However, if the aggressor has the ability to recognize this pattern, it only makes team members a target, thereby reducing the overall effectiveness of the team.

By running a number of simulations in a virtual environment, the evaluators can quickly develop an appreciation of the new equipment's strength and limitations even before the prototypes have been fabricated. By the time actual field testing begins, the group doing the evaluation has had an opportunity to develop a more comprehensive set of tactics to apply. This should result in shorter, more effective field testing.

5.3 Software Environment

The balance of this section includes five subsections which discuss issues related to developing the software environment for the virtual tool. Subsection 5.3.1 describes a typical scenario, which can be executed with the successful completion of the roadmapped effort. The example scenario is presented not only to represent a possible long-term vision for this effort, but also to help *visualize* the concepts and ideas discussed. A functional overview of the complete system is presented in Sections 5.3.2 and Section 0. Section 5.3.4 discusses the software development environment. Subsection 5.3.5 describes the hardware required for this effort and subsection 5.3.6 discusses other considerations regarding the implementation of the virtual tools.

5.3.1 Typical Scenario

Imagine a team of two specialists, Bob and John, responsible for the development of a new piece of personal protective equipment. Each is sitting at an SGI workstation having just completed the preliminary static and dynamic analysis of their most recent design concept. The senior specialist, John, prepares for an interactive tactical session by executing the "Session Configuration Module."

Using this graphical user interface (GUI) in "server mode," John selects all geometric parameters and hardware information for the "proof-of-concept" combat exercise. He walks through the portal of the Natick whole body laser scanner and creates a digital model of himself, both external features and internal anatomy. John's digital human model will be wearing the latest body armor virtual prototype for use in an urban warfare virtual environment. After identifying the graphics hardware he is using, John identifies other network CPU resources available for processing during this session.

Meanwhile Bob, who until now has been supporting John in his design effort, takes on the adversarial role and prepares for this session by using the "Session Configuration Module" in "client mode" to configure his "virtual character." He too walks through the body scanner portal

to create a digital model of himself (however, he edits his to employ a thinner somatype) and selects body armor, weapons, personal equipment, and graphics hardware to use in the virtual environment selected by John.

Once Bob and John have completed the configuration portion of the exercise, some pre-processing is performed by various analysis modules (*JOHN O.*, IUSS, MRSAW (Mission Research Small Arms Weapons), etc.) to load the appropriate solution tables (range of motion, etc.) into memory. After several minutes (time varies with CPU power and scene complexity) the "Session Configuration Module" on each monitor is replaced with a "Run Time Module." With the aid of these modules, Bob and John now "see" the virtual environment through the eyes of their respective "character's" and engage.

John, wearing the latest protective armament design, examines the engagement area by manipulating Virtual John (VJ) via the mouse (or Joystick, dials, etc.). After considering several options, VJ runs across the room and hides next to an open doorway. VBob is in the next room crouched down behind a pile of rubble created from an explosion. VJ quickly enters the room diving and rolling. VBob gets a shot off giving away his location but hitting VJ directly in the chest. Stunned but alive, VJ fires at VBob with deadly accuracy, which ends the engagement.

Bob and John exchange "high fives" as it appears their latest design has performed flawlessly. Just to be sure, they "rewind" the engagement and begin to use the tools available in the "investigate" mode. They are now able to slow the simulation down, change camera views, and look at the engagement in detail. With the simulation replaying, just as VJ reaches the doorway, real John presses the "pause" button and selects "Heat Stress" from the analysis menu. An examination of the results mapped onto VJ reveals that workload, heat stress, and range of motion values are within acceptable limits. This has not been the case with some previous designs. In a similar manner, John and Bob examine VJ after he was shot in the chest. By viewing the results of from the wound analysis, they find there have been no penetrating wounds, but there was evidence of blunt trauma.

VJ survived this engagement using his patented "dive and roll" tactic but would probably not survive an attack from another adversary. Thus, after comparing results of this engagement with those of previous sessions, Bob and John develop an approach to improve the design. Since they only spent about 30 minutes "virtually" testing their latest design, Bob and John will have the rest of the afternoon to work on the next design iteration.

Once Bob and John have identified a design or designs that satisfy all necessary criteria, other evaluators can begin to develop a comprehensive set of tactics to go along with the new protective equipment.

5.3.2 System Overview

The complete system, schematically represented in Figure 24, is made up of a development environment and multiple functional modules. The development environment operates independently of the functional modules. The functional modules are integrated together to form a robust and modular software environment applicable to many types of simulations.

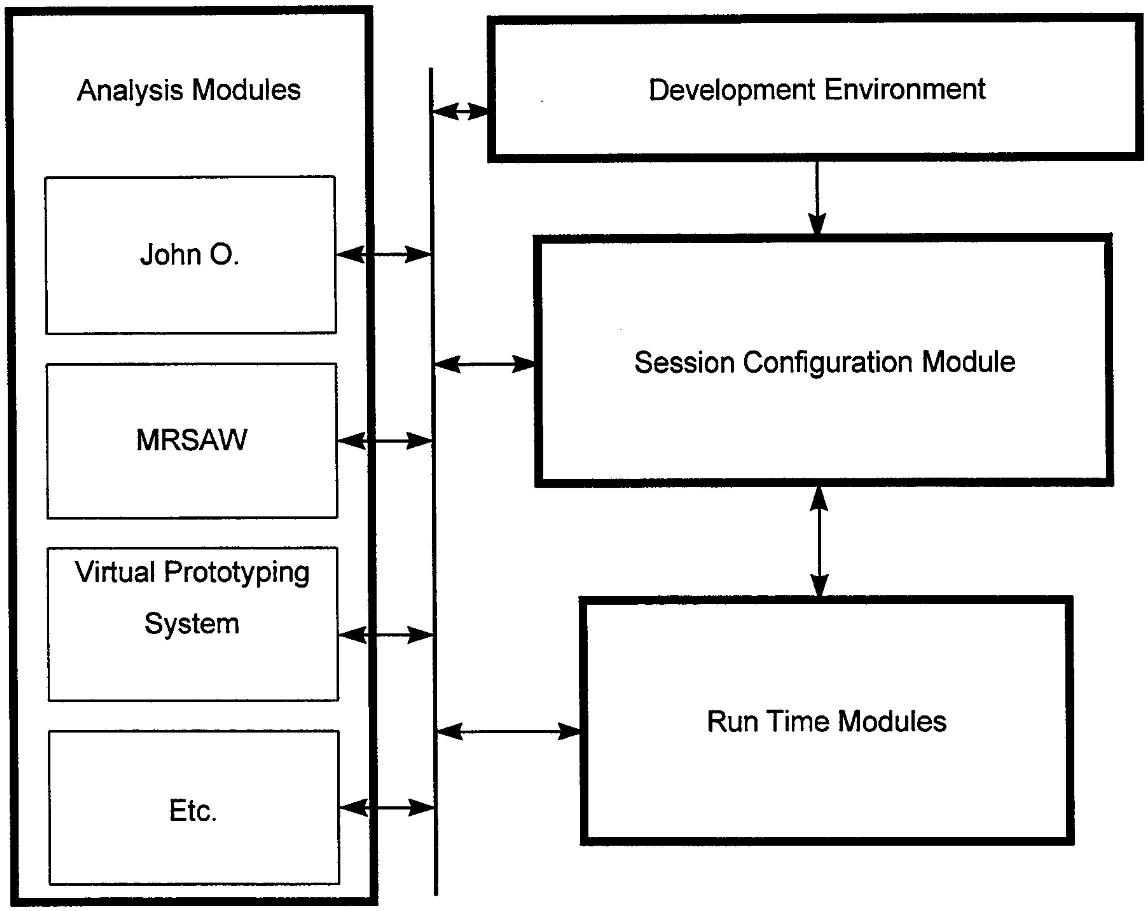

Figure 24. Overview of System

5.3.3 Development Environment

The purpose of the development environment is to enable the creation of new 3D models (weapons, equipment, tools, etc.) and virtual "worlds" (3 story building, subway, parking garage) for use in real time simulations. Some models such as the personal protective equipment or the human body models will be created in one of the Analysis Modules but others may require some final processing in a 3D modeling tool specifically designed for real time use. A tool, which specializes in creating real time simulations, will be required for development of the specific virtual environment used for "testing" the various prototype designs.

One such set of modeling and real time simulation software tools commonly in use in DoD activities is Coryphaeus®. The combination of Designer's Workbench® and EasyScene® provide the core capabilities for developing models and environments for use in real time simulation applications.

An environment consisting of a couple rooms separated by a large open space with a few various walls and doorways, for example, would be created in Designer's Workbench. Other objects (human model, basic personal equipment, workspace) would be created in the Analysis Modules

incorporated into the prototyping system and exported to the proper format for use in the virtual environment. Elements of the simulation would then be selected and "assembled" into the environment model via the Session Configuration Module described next. The Session Configuration Module "compiles" everything together to create a complete Run Time Module as described in subsection 5.3.3.3.

5.3.3.1 Session Configuration Module. Ideally, a graphical user interface should be developed to manage the selection, configuration, and monitoring of all geometric data, analysis data, Central Processing Unit (CPU) processes, and computer hardware necessary for the virtual prototyping simulation. This GUI would essentially run as a shell on top of Coryphaeus EasyScene. When all parameters are properly selected by the user, an "execute" feature will assemble all information into an EasyScene based run time module. This process is analogous to a pre-processor which creates lines of "C" code for a specific purpose and then compiles the code into an executable form of the "C" program. In this example, the executable "C" program is a run time module discussed in subsection 5.3.3.3.

This Session Configuration Module could be designed to be completely Joint Modeling and Simulation System (J-MASS) compliant. The J-MASS Marketplace and compliance criteria are discussed in subsection 5.3.6.1. It is believed that by designing the GUI to be J-MASS compliant from the earliest development stage, no compromise in performance will be necessary.

The Session Configuration Module will allow the user to select the following types of information:

- Human models
- Personal protective equipment
- Weapons and other equipment
- Virtual Environments
- Analysis Methods
- Graphics Hardware being used
- Other available network resources

From the standpoint of human models, since it would be prohibitive to create 3D models for all possible combinations of digital human models, only the most common combinations would be immediately available at runtime. Any "non-standard" digital human will be configured with the graphical interface and information sent to the *JOHN O.* module to build the required geometry. This polygonal geometry will then be loaded into memory for the current session and will then also be added to the list of available human models for future use. More exact and detailed human models could be created using the Natick whole body laser scanner. This data would also be processed by *JOHN O., which* would export the model in the polygon format required by the real time software.

Three-dimensional models of the personal protective equipment will be created either in a CAD package, within the Coryphaeus® modeling environment, or scanned with the whole body laser scanner. Again, once these models have been created the first time they will become part of the library and will be available for future sessions.

A library of vehicles, weapons, and environments will be created much in the same way. Also, since many of the desired vehicles, weapons, and environments have already been created for other DoD and commercial uses, they may only require converting to a new format to be made available for use in a virtual prototyping session.

Depending on which analysis information has been requested by the user via the GUI, specific information will be sent to the appropriate analysis module. The analysis module will in some way affect the data that was sent to it and return new values. The analysis modules are discussed in more detail in the next section.

The ability to identify the graphics hardware being used allows a wider range of users to execute the virtual prototyping software. For example, users who have access to high end SGI Onyx2 level graphics would benefit by receiving higher fidelity models from all the analysis modules and a greater number of "immersed" objects. On the other hand, users on low end graphics hardware would have fewer and lower resolution objects available for the simulation.

From the standpoint of network resources, if the GUI "is told" of the availability of additional processors, it will allow more analysis to be performed as necessary during the simulation. This could also result in higher fidelity graphics quality.

5.3.3.2 Analysis Modules. The analysis modules shown in Figure 24 are a series of stand alone processes that calculate a specific parameter as required for the real time simulation. For example, the *JOHN O.* module combines anthropometry, internal geometries, and dynamic properties to create a 3D human model. The FATIGUE analysis module (and/or IUSS interface), combines 3D human model data, protective system data, and environmental factors to create heat stress distribution for the human model. Still another module, MRSAW uses weapon and munitions data and 3D environment geometry to predict the trajectory of bullets and munitions fired in the virtual environment. Additional analysis modules can be developed and integrated into the overall system at any time with little change to the overall system architecture.

There are two main types of analysis modules; those which process static data and feed results into the simulation during the session configuration phase, and those which require information from the simulation as it progresses to update calculations.

The operation of each analysis module can be managed with the session configuration module discussed earlier or with a dedicated interface. Actually, the dedicated interfaces for each module are what make up the "analysis module manager" section of the session configuration module so it will be a relatively straight process to isolate them for stand-alone use.

5.3.3.3 Run Time Modules. A run time module (Figure 24) is a "compiled" version of all elements necessary for the simulation. Pointers to all geometric data sets, analysis data sets, analysis modules required for real time analysis, and everything else specified with the session configuration module are stored in these files. File formats are a function of the real time software constraints (e.g., Coryphaeus) but typically binary and ASCII files are used.

These run time module files can be re-opened with the session configuration manager to change one or more of the parameters (human model, personal protective equipment, etc.) or they may simply be executed again for a new interactive session. In the new interactive session, the entire 3D environment will be identical to the previous session but any input from external devices (mouse, joystick, etc.) will cause the outcome of the simulation to be different.

During the session, an option can be made available to "record" the entire simulation to disk for playback at a later time. This "playback" file can grow quite large depending on the complexity and length of the simulation. Playback files will be useful as a means of comparing with other similar sessions of the simulation. For example, one could investigate the effect of different combat tactics by keeping everything else constant between sessions. Then by using the session configuration module to display side by side windows, one could view the simulation for various tactics.

Management of all runtime module files is accomplished using the session configuration module.

5.3.4 Software Development Approach

5.3.4.1 <u>User Community Survey</u>. While this report lays the foundation for a very robust virtual prototyping system, it is believed that significant beneficial information can be realized from identifying a "panel" of potential users of the software environment. This panel could be valuable to help determine desirable features and capabilities for the virtual prototyping tool. It is a good idea to include the commercial sector in this survey if we want to be able to satisfy the needs of a much larger market than just DoD related activities.

5.3.4.2 <u>Development Approach</u>. The software development approach will be similar to that used in the MRC STRICOM Phase II SBIR project, see Section 1.3. In the proposed development effort a hybrid of *Commercial Off-The Shelf* and *wrap-around* custom software will be employed. Coryphaeus® is presently the leading candidate for providing the core visualization and real time simulation capabilities. A custom software development effort will be utilized to create the desired capabilities, which are not available in Coryphaeus®.

5.3.4.3 <u>Articulating Human Model</u>. An articulating human model will be developed for this effort. This model will allow for articulation within the virtual environment and will be able to simulate various interactions of the individual with the space he or she is located in. Each limb or movable part of the human model will be treated as a separate 3D model within the virtual environment. A system parenting one limb to another will be utilized to minimize the amount of data that must be communicated between modules. In this way, parenting arms and legs to a torso for example, only the x, y, z translation and rotation coordinates of the body center of mass, x, y, z, coordinates for the axis of rotation for each limb, and the angles of limb rotation about that axis will be required. This approach entails a much smaller communication bandwidth and data stream than by specifying a complete geometric database for each time step that the object changes position. In this case the bandwidth of the communication data stream is much lower.

The geometry will be made of triangular polygons with simple materials and textures. Sufficient polygonal density will exist to ensure adequate representation of the digital phantom. The data

files describing the digital phantom will contain all data structures required by the visualization tool (e.g., Coryphaeus®): Three-dimensional coordinates for each vertex, vertex connectivity table for each polygon, axis of rotation and rotation constraints for each movable element, and material, and texture definitions. These files will be created during the Session Configuration phase of the simulation.

Injuries or limitations in range of motion due to protective equipment can be simulated by imposing rotation constraints on the affected joint or axis of rotation. These "limitations" would be computed by one of the Analysis Modules. For example, if the "player" is shot in the left shoulder, and the damage to the shoulder (calculated by *JOHN O.*) would result in a disabled left arm, the "player" would not be able to use the simulated left arm or hand to manipulate any virtual device or weapon.

5.3.5 Computer Hardware

It is desirable to have a platform independent solution for the scene generation to ensure a system that is useable by the largest possible audience. However, graphics performance requirements of state-of-the-art commercially available simulation software usually restrict the computer platform to Reduced Instruction Set Computer (RISC) based workstations and exclude the use of Pentium based personal computers.[54] Even at the workstation level, some software vendors do not develop their code to run on all platforms but restrict the operation to specific hardware which satisfy unique performance requirements. Thus, the computer platforms selected for this effort will depend on the requirements of the software environment chosen.

In the past few years, Silicon Graphics has been one of the leaders in the visual computing market and utilized proprietary graphics libraries to accomplish their incredible performance. For competitive reasons, SGI started to license its' graphics libraries (OpenGL) and now SGI like performance is available on a wider range of vendor equipment. Since all hardware graphics performance numbers change so dramatically with time (hardware cycle times are approximately eighteen months or less), the cost of the hardware environment required to use the virtual prototyping software will not be known until close to the completion of the Phase II effort.

While the term "real-time simulation" is often used in this report, that term does not say anything about the quality of the graphics. It only specifies that the events will occur on the computer in the same amount of "clock" time as they would occur in real life. The better the graphics hardware and the more CPUs available to handle auxiliary calculations, the higher the "frame rate" will be and therefore the smoother and more believable the motion.

5.3.6 Implementation Considerations

There are other development and communication environments of interest for implementation of the proposed system. While the following is not an exhaustive list, it represents a couple of the most significant environments.

5.3.6.1 Joint Modeling and Simulation System (J-MASS). It is current DoD policy to use COTS whenever it meets DoD requirements. The application of this policy to modeling and simulation has resulted in the concept of the Joint Modeling and Simulation System (J-MASS). J-MASS is an open systems architecture with the capability for the Simulation Support Environment (SSE) to be expanded by the addition of site specific software.

J-MASS is also envisioned as the Air Force common modeling and simulation architecture. As the DoD High Level Architecture (HLA) evolves, J-MASS will comply with those standards. Wright Laboratory and the J-MASS Program Office are developing the concept of the "J-MASS Marketplace," where industry would build commercial tools to work with J-MASS in response to customer demand. A J-MASS product release will provide the core capabilities to meet the needs of many J-MASS users, but the unique demands of many organizations would be satisfied by industry developed applications. The Marketplace concept avoids the high cost of DoD wide licenses and permits commercial market competition to satisfy individual organization requirements.

There are two aspects to J-MASS compliance: support and structural. Support is the data necessary for the software to be used by a member of the J-MASS community. Structural compliance has to do with how the software initiates execution and how it communicates with other J-MASS compliant software. Structurally J-MASS compliant tools must

- Receive User Commands via the J-MASS Graphical User Interface
- Initiate execution across the J-MASS Tool Back Plane
- Communicate through the J-MASS Tool Back Plane
- Handle data via the J-MASS Modeling Library capability

To insure supportability, J-MASS compliant tools must:

- Execute on the J-MASS target workstations
- Have a Software User's Manual
- Have a Test Report with test drivers
- Provide an abstract and facet terms for the M&S Reuse Library clearinghouse
- Provide files for hypermedia on-line J-MASS Help in HTML format
- Have an available support structure so that J-MASS users can get assistance when required
- Have a model (or some other piece of software) that can be used by the J-MASS Customer Support Center to isolate anomalies between the new tool and J-MASS

The goal for J-MASS is field extensibility – the ability for the user to add various *Commercial Off-The Shelf* and *Government Off-The Shelf* tools as required for that user site and to be able to do it as easily as a personal computer or Macintosh user adds word processor software to a home or office computer. Field extensibility would require several enhancements to the J-MASS SSE.

These enhancements would include capabilities to dynamically maintain the J-MASS Graphical User Interface, incorporate new COTS applications or delete existing ones, setup application environments, a customize feature to tailor each mode and move application icons between windows, and to dynamically create new Modeling Library data types for new applications. A Tool Developer's Manual would be required to provide all necessary information for a third party to design, develop, test and integrate a tool into the J-MASS architecture. The manual would

include requirements and methodology for interface and integration, message and control structures, documentation, and testing.

Since J-MASS is constantly evolving, the latest compliance specifications would have to be identified and implemented during the Phase II development effort.

5.3.6.2 Intranet or Internet Capabilities. With the extreme popularity and capability of the World Wide Web, and the unlimited availability of access to the Internet and Intranet, it is possible to envision a new design and development environment for this effort. A web site "shell" could be created to manage all the design concepts and analysis results for the virtual prototyping efforts. A typical page could consist of a small image of the device and links to the files resulting from all the analysis that has been completed for the specific design. If the hardware the person was using was capable of running the module that creates the analysis results (MRSAW, MRCMAN, *JOHN O.*, Coryphaeus) then actual results could be viewed. Otherwise, results could be saved as an image (JPEG, pic, etc.) or QuickTime® movie files. Also, any reports for the design could also be maintained in the same area. Many companies are beginning to use the Internet and World Wide Web in this manner as an Intranet.

All the technology necessary to implement this capability is currently available for anyone who has access to the Internet. The only issue that needs to be addressed is that all "analysis" modules must be able to save image and/or QuickTime® movie files.

5.3.6.3 Stand Alone Weapons Effects Server. A more reasonable scope for the Phase II effort might be to develop a scaled down version of the GUI mentioned previously to drive just the *JOHN O.* type of analysis module. This GUI would be available to anyone on the J-MASS back plane or anyone on the DoD Internet or Intranet.

6. PHASE II PLAN

The Phase I effort developed a roadmap for development of a digital human model suitable for virtual prototyping of protective equipment and as a character in a virtual environment. This roadmap obviously exceeds the resources of a Phase II SBIR effort. However, the roadmap will serve as a basis to focus initial development consistent with Phase II resources and for planning Phase III follow-on efforts.

The Phase II human model will employ detailed body contour data obtained from full body scanners onto which an anthropometrically accurate 3D digital model is created. Landmarks on the body surface will be used to map internal anatomy using both the *JOHN O.* model, Visible Human data, and existing Visible Human segmented data (e.g., VOXELMAN). Mass properties of body segments and joint equations of motion will be incorporated in order to describe body dynamics of the digital human. The Articulated Total Body Model (ATBM) will be used for this purpose.

Models of protective equipment performance will be extended to describe interaction of a range of military projectiles with multilayered soft fabric body armor, with and without rigid insets. Models of penetrating wounds from ballistic impact, blunt trauma from non-penetrating projectiles, and kinematic trauma (body collision with the workplace) will also be incorporated into the digital human model. Penetrating wound models will be imported from MRC's virtual surgery simulator support projects. Criteria for kinematic trauma will employ Viano's viscous criteria and other data from the auto industry. Blunt trauma from non-penetrating projectiles will use data obtained from MRC's Sensate Liner effort and models being developed to support that effort. Anecdotal medical information will have to be mined from other sources to develop appropriate injury criteria.

Finally, a software architecture will be developed which includes at least three design cycles. The first cycle will be detailed static design which evaluates reduction of joint moment generating capability, thermal load, stability on various terrains, increase in work associated with movement, pressure points under different equipment loads, and casualty reduction potential to prescribed threats. The second cycle consists of a dynamic analysis, which includes the digital human accomplishing tasks with the equipment in a virtual environment. Parameters relative to equipment performance and the physical state of the virtual humans can be displayed as a function of time. Additionally, the dynamic analysis can be stopped at any point in the scenario to perform detailed static analysis of the digital human or to compare performance with previous dynamic simulations. The final cycle is non-virtual field testing.

6.1 Visualization System

An integrated part of the Phase II effort is to provide the foundation of a real time visualization system as an extension of the dynamic analysis of protective equipment (see Section 5.2). The underlying process of dynamic analysis is to apply the methodologies of Static Analysis to appropriate models as they are moved through a threat environment. As such a visualization system is not required to obtain pertinent data on any changes in mission effectiveness. However,

such analysis generates a large amount of data, the analysis of which is difficult and time consuming. A visualization system provides an effective, intuitive form of data reduction for two different end user groups.

The first user group is the designers of the protective equipment. By being able to quickly review multiple engagements, the designers will be able to identify patterns and trends in the way that the equipment is employed, and the resulting casualty mechanisms, which are useful in improving the equipment design.

The second group is the infantry soldier. Every change of equipment imposes new limits on the combatants who use the equipment. Changes in bulk, mass, load distribution, signature, or heat transfer effect the performance of combatants. Changes in the performance of the protective equipment effect the rate and type of casualties. Further, advanced protective equipment may not be merely parasitic material but may provide entirely new capabilities, e.g., DLA/DARPA/ NaRD/MRC's Sensate Liner System (SLS).[55] These factors could affect selection of tactics. Since a significant percentage of the user community who would have pertinent input to this process have other duties which preclude detailed analysis of tabular data, a visualization system provides an effective means of data representation. Since the infantry soldier is ultimately the protective system designer's "customer," the visualization system will also provide a new common basis of collaboration between the designer and end user. The proposed system will take the notion of "Concurrent Engineering," which has largely focused on concurrent development by disparate technical specialties, to its logical conclusion by integrating the infantry soldier into the virtual design process.

While the full resolution *JOHN O.* model format is appropriate for static analysis, it entails too great a work load on current graphic display systems when used in a realistic tactical scenario for dynamic analysis. Therefore, one of the firsts tasks of Phase II will be to determine an appropriate methodology for reducing the surface model of *JOHN O.* to a simpler polygonal model suitable for real time rendering. While there are several polygon reduction systems available, including systems designed to work specifically with the Cyberware scanner, the final selection will require integration into the *JOHN O.* format for proper maintenance of joint positions for movement and reference points for proper interpretation of injuries. The automated creation of models with multiple levels of detail will provide significant flexibility in rendering real time visualizations.

The selection of the *JOHN O.* model is a major computational enhancement for real time dynamic analysis over other models, such as *JACK*. The objective of *JOHN O.* is the effective representation of anthropometrically correct models with appropriately placed internal structures. *JACK*, using a radically different data structure, was designed to provide an effective research tool for human factors design. The result is that *JACK* has many features, such as fully articulating hands, with a great deal of complexity, while adding no useful detail for applications in this effort.

Given the complexity of scenarios appropriate to dynamic analysis, the current generation of graphics systems will be limited to less than 2000 polygons per model. Under most conditions the models will have to be rendered with less than 1000 polygons each to maintain a 30 Hz update rate on the visualization system. However, the dynamic analysis system does not have to

perform in strict real time. All of the tools currently being examined for real time application are based on the Silicon Graphics, Inc. *Performer®* tool set. *Performer* provides for dynamic load leveling. When scene complexity increases, *Performer* automatically shifts the controlling ranges of the different levels of detail to reduce the scene complexity to a point where the desired frame rate can be maintained. It therefore will be possible to provide two independent controls to the user: (1) Define a target frame rate; and, (2) Define the real time scale factor. Reducing the target frame rate allows more time per frame for spatial detail to be rendered. Reducing the time factor increases the temporal resolution of the simulation.

During dynamic analysis, the most critical portion of the analysis is accurate collision detection. In this context, collision detection has five aspects, which are, in increasing complexity: fixed, ballistic, dynamic, confined space, and snags. Fixed collision is the ability to represent collisions between a modeled combatant and continuous solid surfaces, such as the ground and walls. Ballistic collision detection starts with an event that generates ballistic particles (i.e., an explosion or a weapon being fired). The ballistic particle has a parametric trajectory, which is a function of time. The determination of ballistic collision requires that the position of the modeled combatant be interpolated to the moment of impact in order to obtain accurate analysis of impact placement and the resulting damage. Within the context of the Phase II effort, only fixed and ballistic collision will be addressed.

Dynamic collision is a representation of interaction with an unstable surface, such as rubble or gravel. The non-linear behavior of the surface material puts a suitable representation beyond the scope of a Phase II effort. While fixed object collision takes into account interactions between the combatant and a solid surface, it does not properly represent the interaction of the combatant with multiple simultaneous constraining surfaces. The modeling of how a combatant moves through a confined space, such as a hole or through debris, requires extensive modeling of range of motion and mobility, as well as the size, of the combatant. A more detailed modeling of the combatant's equipment and flexibility of that equipment is also required for accurate determination of mobility. Another aspect of the dynamic model is determining which pieces of equipment the combatant removes to gain access to a space. Once confined space analysis is accomplished, it must be extended to account for "snags." While the combatant may fit through a space, the presence of any projection, which may catch on clothing, or equipment may in fact make the space impassable. This level of analysis is also beyond the scope of the Phase II effort.

As a further aid to analysis, each of the models being used in a scenario will have graphic readouts, similar to the *Integrated Unit Soldier System* (IUSS) developed by Simulation Technologies under Natick sponsorship. These readouts will indicate designated data, such as fatigue level, thermal load, and casualty state and could conceivably use data directly from *IUSS* in addition to data from *JOHN O.* and the virtual environment. The data of previous runs, either individual or statistical groups, can be shown with the current run data to allow a quick comparison of performance.

One limitation of the Phase II effort will be the user interface. As part of a Phase III effort all aspects of the user interface will need improvement. This ranges from the designers' ability to specify and place protective materials, to defining the appearance, function and wearing

characteristics of that equipment, to defining the scenario and the behavior of characters within the scenario. Table 4 compares the nominal scope of Phase II versus a follow-on Phase III effort.

Table 4. Phase II Nominal Scope versus Phase III

PHASE II VIRTUAL CHARACTER PROCESSOR	PHASE III VIRTUAL CHARACTER PROCESSOR
Polygon reduction	Support for higher resolution models
Animation and articulation	Automated support for virtual equipment
First order range of motion	Improved range of motion limits
Fixed object collision detection	Dynamic collision detection
Ballistic collision detection	Confined space collision detection
Impact indication	"Snag" collision detection
Damage indication	Enhanced multi-player environment
Graphic readout	Improved user interface

6.2 Anthropometry and Anatomical Modeling

In Phase II, the Human Model Roadmap (Figure 7) will be implemented using many resources already developed or in progress, and minimizing the need for new computer software and database development.

For the first part of the roadmap the major work will be in insuring that the anthropometric models computed from databases such as ANSUR are appropriate to the personnel being modeled in virtual prototyping applications, and that the data formats are compatible step-by-step. While the Air Force's (AF) Multivariate Accommodation Model (MAM) is not yet published, and the Army adaptation of it is still work-in-progress, we will work with the service personnel to influence the programs and ensuring utility for this application. It is anticipated that our parallel work will involve both software development and statistical analysis validation. Dr. Beecher has a long history of working with the AF (Gregory Zehner) and Army (Brian Corner) personnel involved in this project.

The computed anthropometric data sets will be used as input for programs such as GEBODIII and FRNKNSTN. Modifications of these two programs will be used to compute the 3D surface, joint locations, and inertial properties for the human model. FRNKNSTN has been used in the past with sets of full body surface stereophotogrammetric data which were recorded at approximately one inch resolution (space between points).[56] These data sets of 31 men and 46 women spanned substantial ranges of size and shape. Not only were the surfaces recorded, but a large number of pre-marked landmarks were also digitized. These landmarks for the most part defined segmentation planes and segment local reference 3D axes. The surface data was broken down into body segments, and the volume moments and center were computed.[57] FRNKNSTN reads in these analyzed data sets, then computes joint centers and axes. Modifications of FRNKNSTN have been used to re-scale the proportions of individual body segment surface data, then assemble the segments from different individuals to form a hybrid subject data set that conformed to an anthropometric model. The application was the design for new USAF crash test mannequins (ADAM). This is what will be done for the virtual prototyping effort, except that we

will automate the computation and production of proportioned body segment surfaces and their articulation.

GEBODIII has the statistical model to proportion much of the linear geometry (lengths, circumferences, breadths) of body segments. Currently it's output is in the format of the Articulated Total Body Model (ATBM) maintained by the USAF. For this effort, GEBODIII will be incorporated into FRNKNSTN, and the output format will be compatible with the next step, the *INTERNAL STRUCTURE MODELER.*

The *INTERNAL STRUCTURE MODELER* (ISM) will be the focus of new software development. The need here is for a program to input the body surface, joints, and inertial properties, and generate a model of the internal structures, scaled and proportioned to fit. Currently, no such software is known to exist or known to be in development. As the input data will be surface segmented into arm, leg, thorax, etc., the data used by the ISM will also be divided by body segments. The internal data will consist of sets (probably derived from the Visible Human project) previously segmented into internal structures such as organs and tissues. For each segmented organ or tissue, rules will be attached concerning its capacity to be re-scaled or reshaped by the shapes of the surface data in which it will be encased. Applying these rules when scaling and shaping will properly fit the internal structures to the surface. The output of the ISM will be a data set in *JOHN O.* format.

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